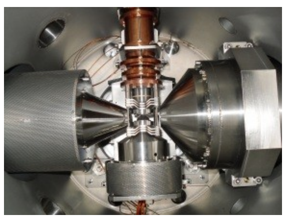
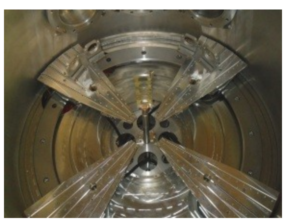


Highly uniform magnetic field coil design for the n2EDM experiment at the Paul Sherrer Institute

P. Flaux, T. Lefort, G. Ban, D. Goupillière, Y. Lemière, B. Dechenaux

nEDM2017 Workshop

October 15-20, 2017 Harrison Hot Springs

Summary

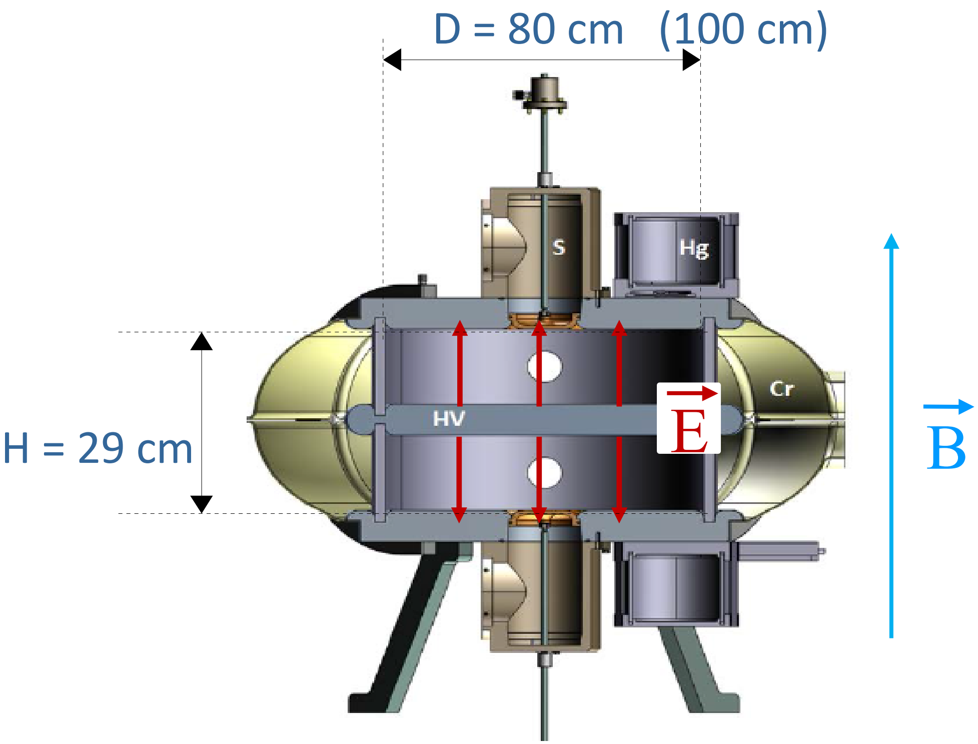
Purpose of a uniform magnetic field

→ $H = -\boldsymbol{\mu}_n.\mathbf{B} - \mathbf{d}_n.\mathbf{E}$

→ 2 configurations : **B** // **E**, **B** ∦ **E**

→ neutron EDM : $d_n = h(f_{n\uparrow\uparrow} - f_{n\uparrow\downarrow})/4E$

→ statistical error : $\sigma(d_n) = \hbar/(2\alpha ET\sqrt{N})$



→ Need a system producing a very uniform magnetic field B
- → In order to avoid neutron depolarisation
- → In order to suppress systematics effects (motional EDM)
- → In order to maximize statistical sensitivity

Uniformity requirements

Field at the center of the coil	B_0 = 1 µT
Neutron depolarisation[1] (< 2 %)	$\partial_x B_z = G_{1,-1}$, $\partial_y B_z = G_{1,1} < 8$ pT.cm^{-1}
Statistical sensitivity : RF-pulse ($\alpha_{loss} < 2$ %)	$\partial_z B_z = G_{1,0} < 0.7$ pT.cm^{-1}
^{199}Hg motional false EDM corrected with crossing point technique[2] $d_n^{false} < 5.10^{-28}$ e.cm	$G_{1,0}$ corrected $G_{3,0} < 3.3.10^{-5}$ pT.cm^{-3} $G_{5,0} < 1.1.10^{-8}$ pT.cm^{-5} (D = 100 cm, H = 12 cm, H' = 17 cm)

[1]C. L. Bohler and D. D. McGregor, PRA 49 MC Gregor (1994), https://doi.org/10.1103/PhysRevA.49.2755

[2]G. Pignol, S. Roccia, Electric-dipole-moment searches: Reexamination of frequency shifts for particles in traps, Phys. Rev. A 85 (4) (2012) 042105

How is produced the B_0 field

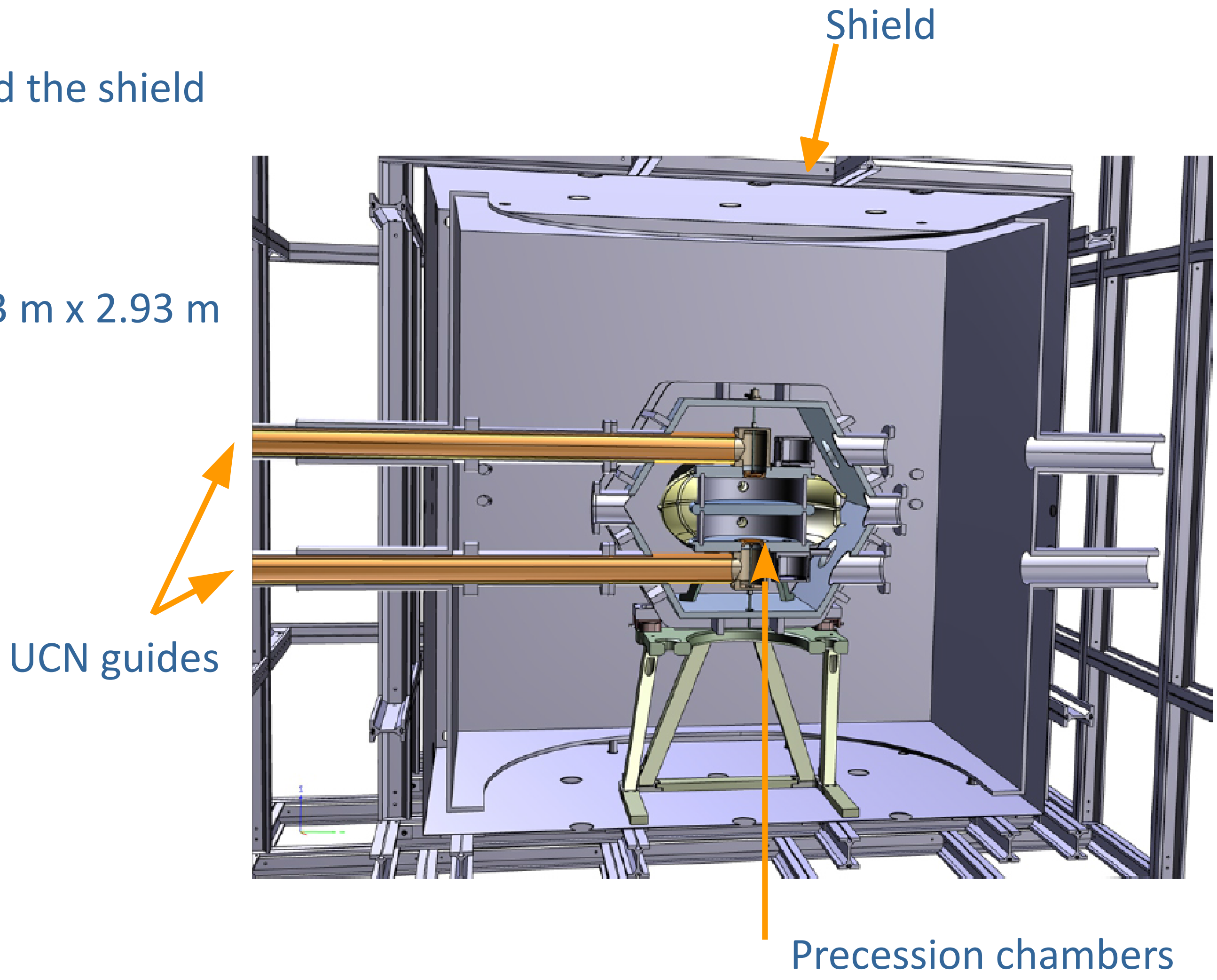
→ B_0 coil is inside the shield

→ Field produced by the coil and the shield

First Layer of Mu-metal Shield :

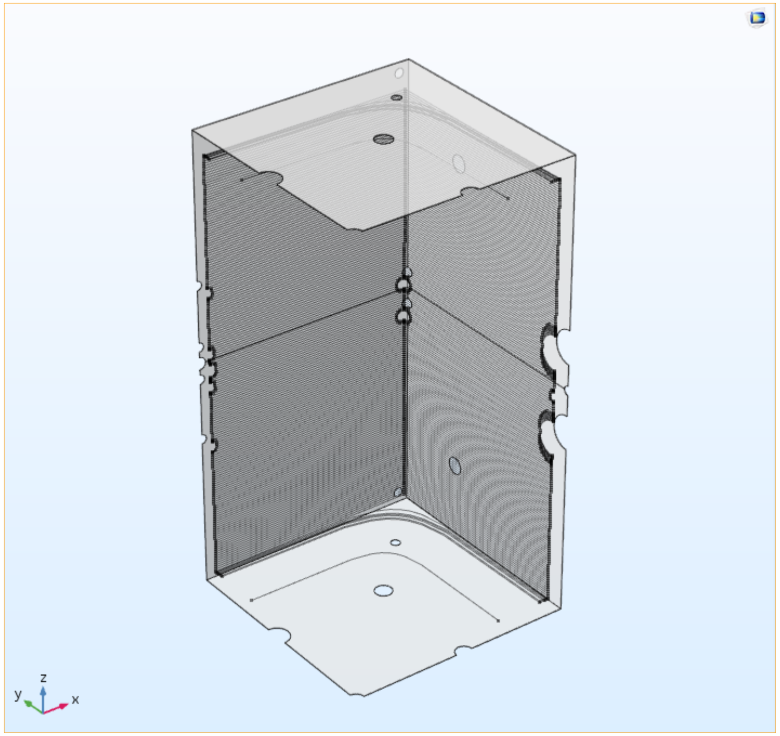
- Dimensions : 2.93 m x 2.93 m x 2.93 m
- Thickness : 3.75 mm

Simulation made with
COMSOL software (FEM)



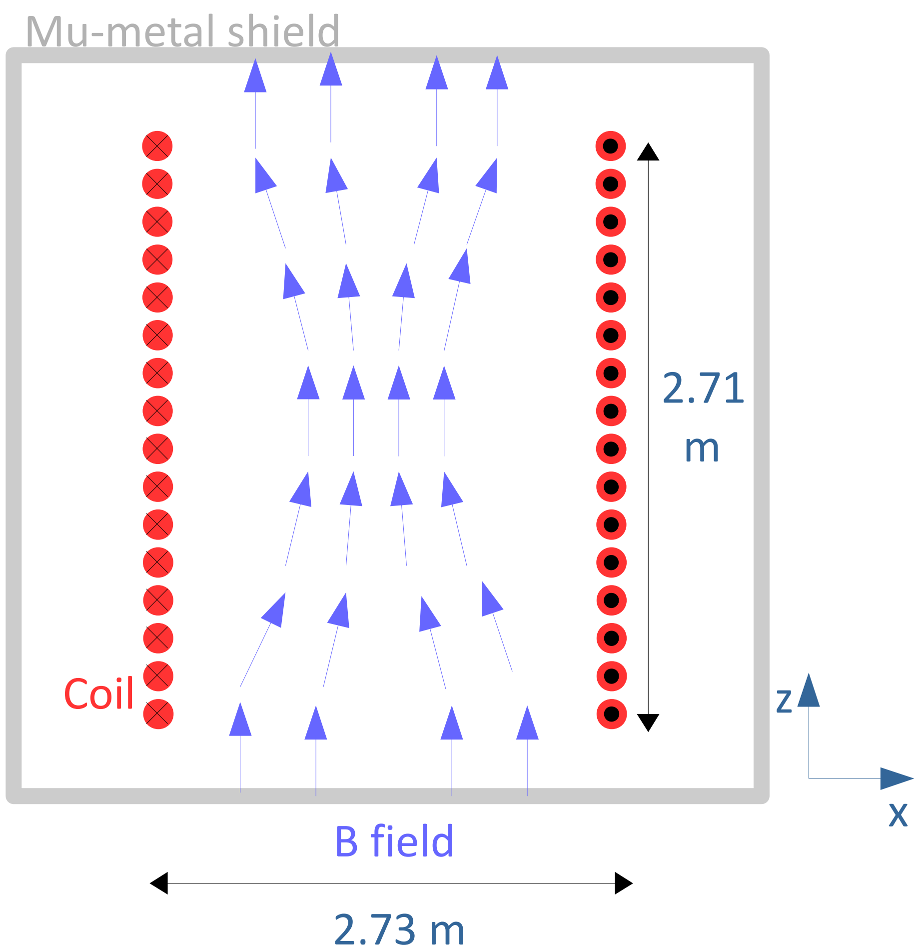
B_0 coil design in the shield

B0 coil : Cubic Solenoïd + holes by pass ...



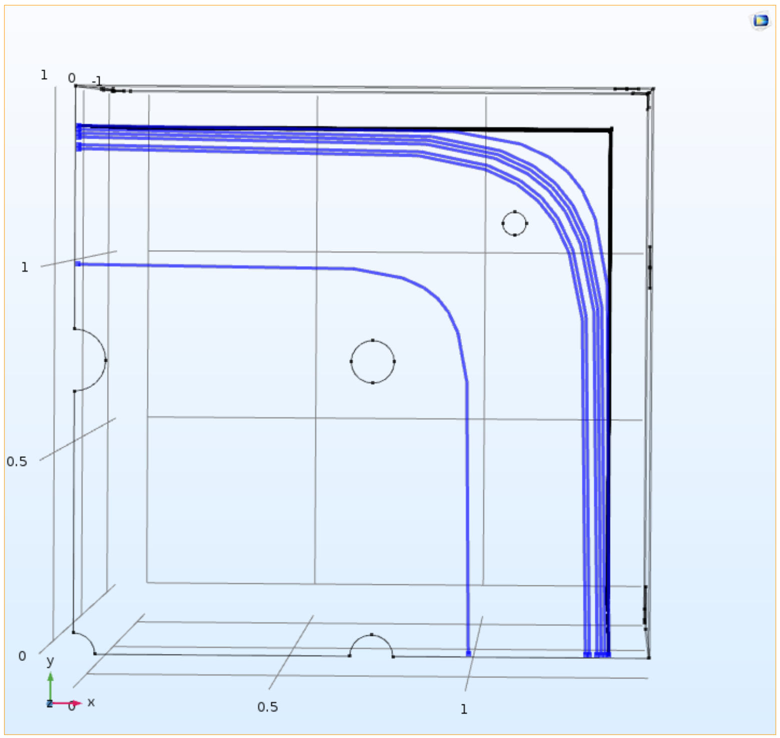
1/4th of the B_0 coil + first layer of the shield

Side view



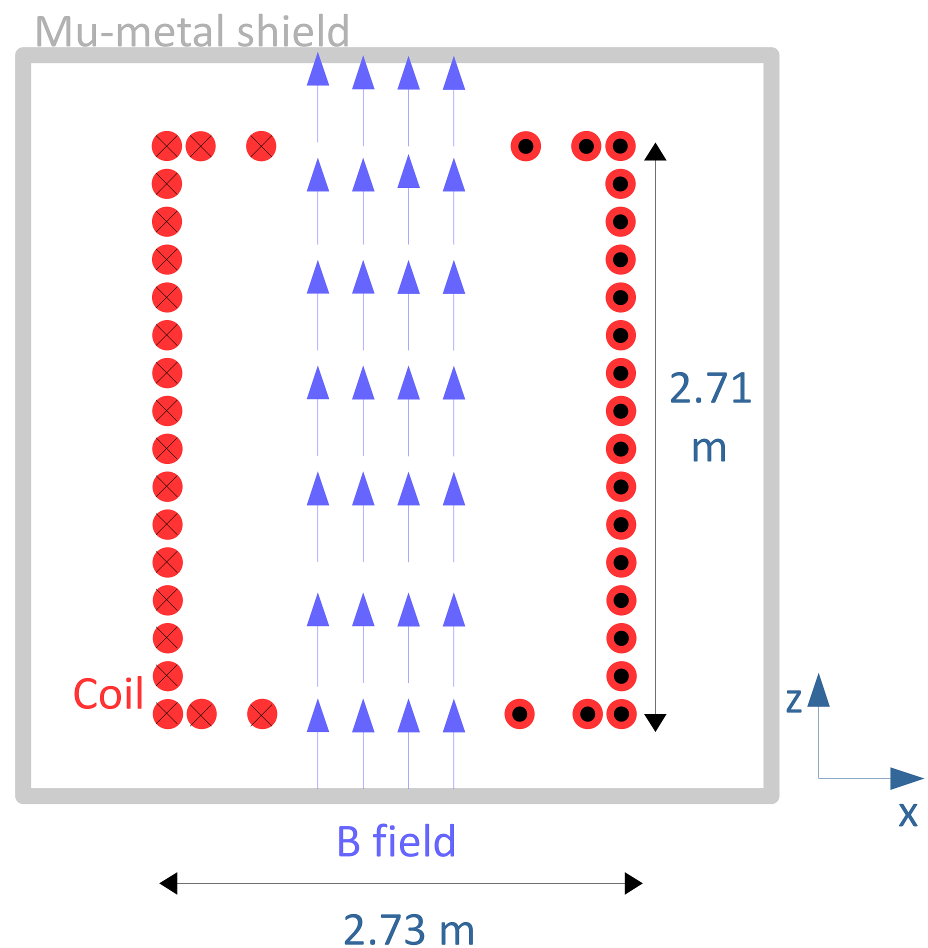
B_0 coil design in the shield

B0 coil : Cubic Solenoïd + holes by pass
+ Endcaps wire loops

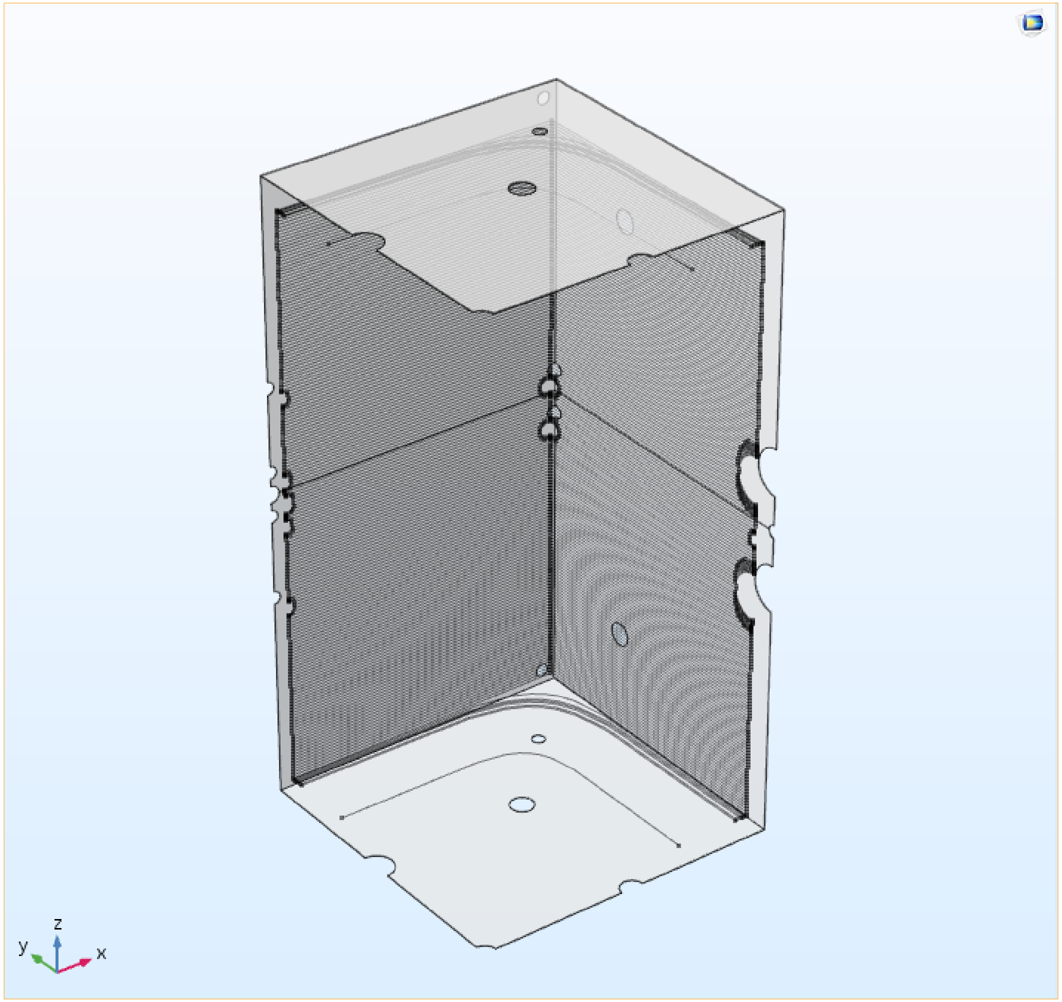


Wire loops « Lamé Curves » at the endcaps
(Top View)

Side view



B_0 coil design in the shield



1/4th of the B_0 coil + first layer of the shield

Coil Side	2730 mm
Coil Height	2710 mm
Wire spacing (side)	15 mm
Number of loops (side)	181
Number of loops (endcaps)	7 x 2
Number of loops (total)	195
Wire current	11.975 mA
Wire length (total)	~ 2100 m
Resistance ($Ø_w$ = 1,5 mm, copper)	~ 20 Ω

Lamé curves:

$x = a.\cos^n(\theta)$;
$y = a.\sin^n(\theta)$;

with

$\theta \in [0,\pi/2]$.

a (mm)	n
1365	0.25
1355	0.3
1345	0.3
1335	0.3
1315	0.3
1305	0.3
1005	0.25

B_0 coil design in the shield

Simulated coil : 3 symmetric and antisymmetric current plans
→ XY plan at z = 0 m (symmetric)
→ XZ plan at y = 0 m (antisymmetric)
→ YZ plan at x = 0 m (antisymmetric)

} 1/8th of the coil is simulated

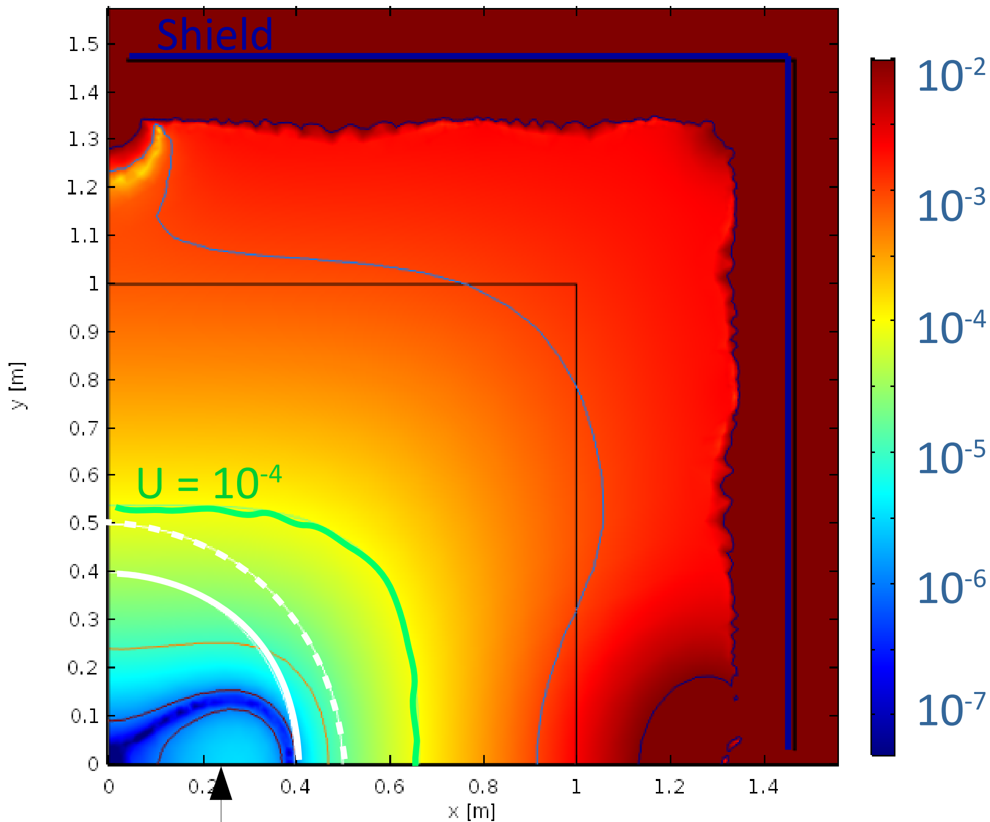
		Field Components		
		Bx(x,y,z)	By(x,y,z)	Bz(x,y,z)
Symmetries	X → -X	- Bx(-x,y,z)	By(-x,y,z)	Bz(-x,y,z)
	Y → -Y	Bx(x,-y,z)	- By(x,-y,z)	Bz(x,-y,z)
	Z→ -Z	- Bx(x,y,-z)	- By(x,y,-z)	Bz(x,y,-z)

Field symmetries

Field Uniformity of the B_0 coil

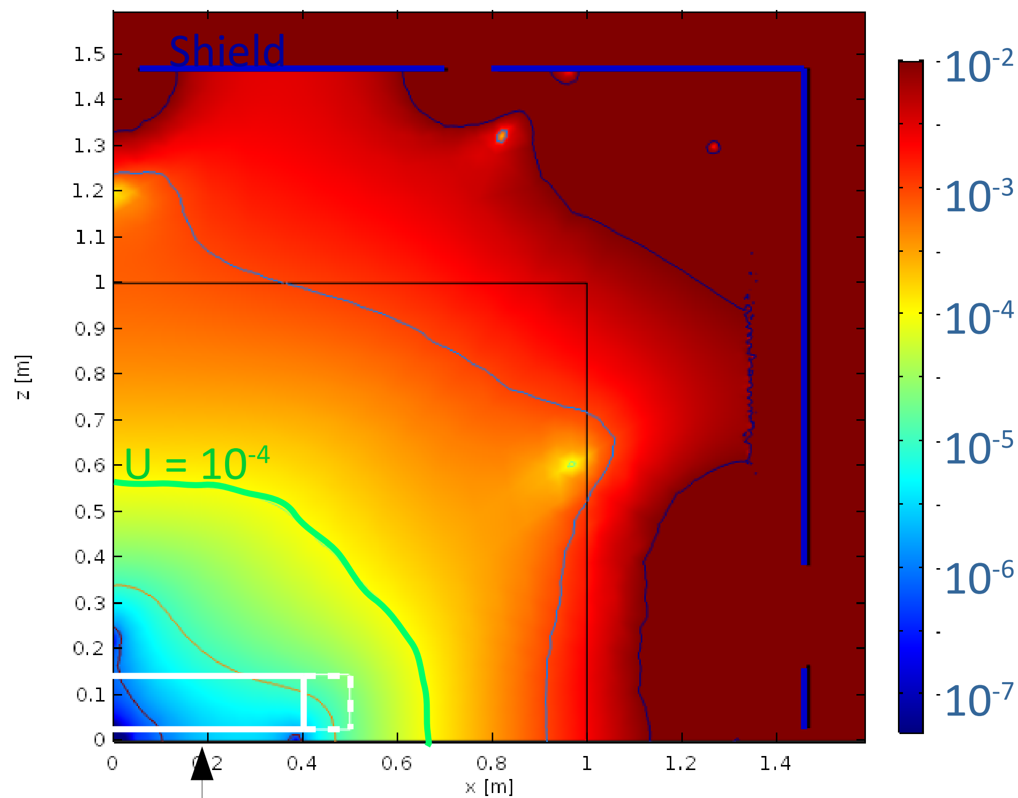
$$\text{Uniformity}: U(\vec{r}) = \frac{|\vec{B}(\vec{r}) - \vec{B}(\vec{0})|}{|\vec{B}(\vec{0})|}$$; B(0) = 1.00002 μT

Horizontal plane (z = 0 m)



Precession Chamber

Vertical plane (y = 0 m)



Precession chamber

U(**r**) < 10^{-4} inside the chamber (∅ = 80 cm)

Harmonic Decomposition

→ Magnetic field can be expressed as a linear combination of harmonic polynomials Hx, Hy, Hz

Magnetic Field at r →

$$\mathbf{B}(\mathbf{r}) = \Sigma_{l,m} G_{l,m} \begin{pmatrix} \mathbf{H}_{x,l,m}(\mathbf{r}) \\ \mathbf{H}_{y,l,m}(\mathbf{r}) \\ \mathbf{H}_{z,l,m}(\mathbf{r}) \end{pmatrix}$$

← Harmonic polynomials of degree l at r

Gradient Amplitude (l,m)

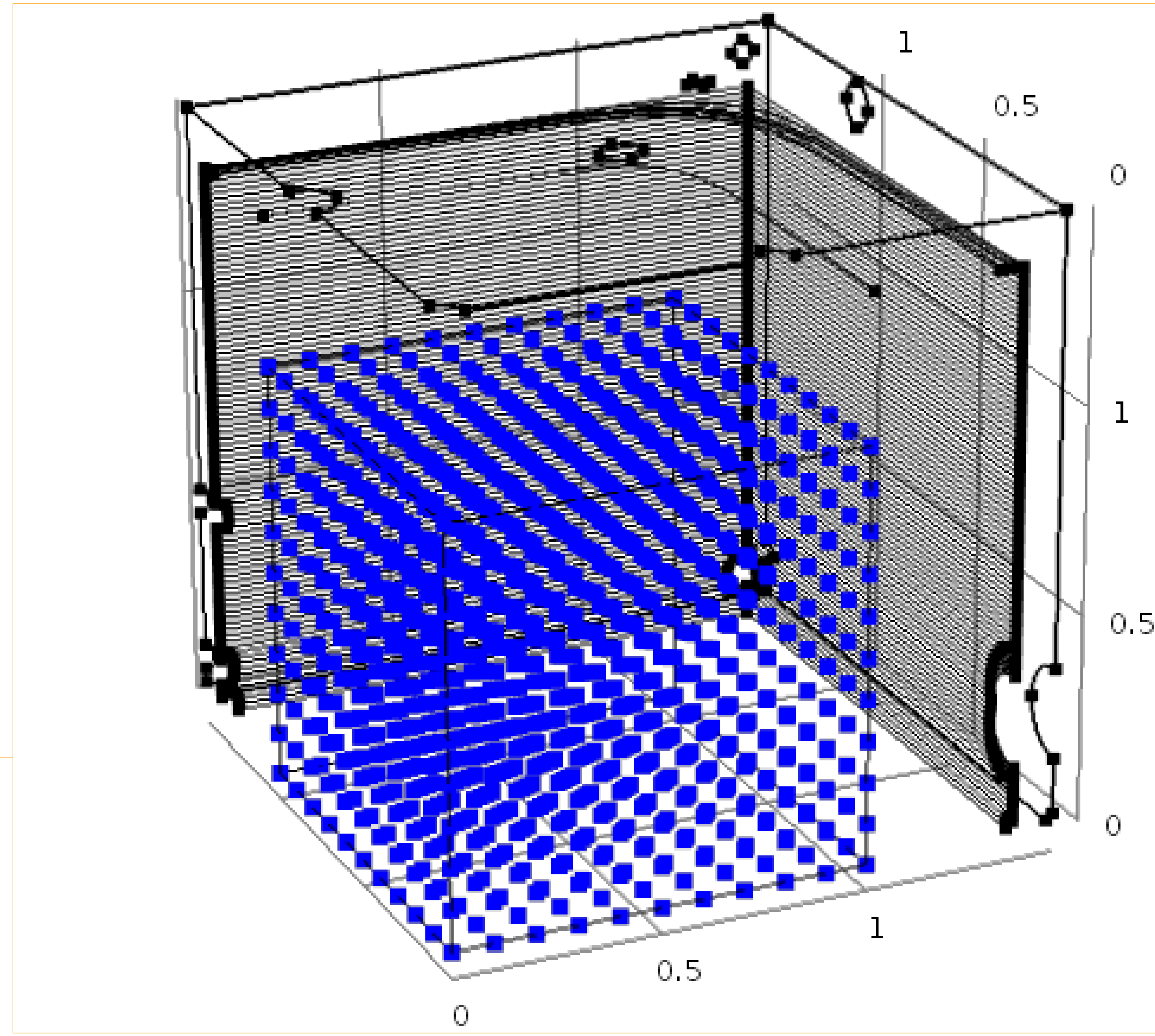
l	m	Hx	Hy	Hz	n°
0	-1	0	1	0	1
0	0	0	0	1	2
0	1	1	0	0	3
1	-2	y	x	0	4
1	-1	0	z	y	5
1	0	-x/2	-y/2	z	6
1	1	z	0	x	7
1	2	x	-y	0	8
2	-3	2xy	$x^2 - y^2$	0	9

Single Value Decomposition method (SVD)

B

$$\begin{pmatrix} B_x(0) \\ B_y(0) \\ B_z(0) \\ B_x(1) \\ B_y(1) \\ B_z(1) \\ \dots \\ B_x(n) \\ B_y(n) \\ B_z(n) \end{pmatrix}$$

Bx, By, Bz components
At several points



Single Value Decomposition method (SVD)

B **H**

$$
B = \begin{pmatrix} B_x(0) \\ B_y(0) \\ B_z(0) \\ B_x(1) \\ B_y(1) \\ B_z(1) \\ \cdots \\ B_x(n) \\ B_y(n) \\ B_z(n) \end{pmatrix}
\qquad
H = \begin{pmatrix}
H_{x01}(0) & H_{x00}(0) & H_{x01}(0) & \cdots & H_{x78}(0) \\
H_{y01}(0) & H_{y00}(0) & H_{y01}(0) & \cdots & H_{y78}(0) \\
H_{z01}(0) & H_{z00}(0) & H_{z01}(0) & \cdots & H_{z78}(0) \\
H_{x01}(1) & H_{x00}(1) & H_{x01}(1) & \cdots & H_{x78}(1) \\
H_{y01}(1) & H_{y00}(1) & H_{y01}(1) & \cdots & H_{y78}(1) \\
H_{z01}(1) & H_{z00}(1) & H_{z01}(1) & \cdots & H_{z78}(1) \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
H_{x01}(n) & H_{x00}(n) & H_{x01}(n) & \cdots & H_{x78}(n) \\
H_{y01}(n) & H_{y00}(n) & H_{y01}(n) & \cdots & H_{y78}(n) \\
H_{z01}(n) & H_{z00}(n) & H_{z01}(n) & \cdots & H_{z78}(n)
\end{pmatrix}
$$

Harmonic polynomials values for the same points

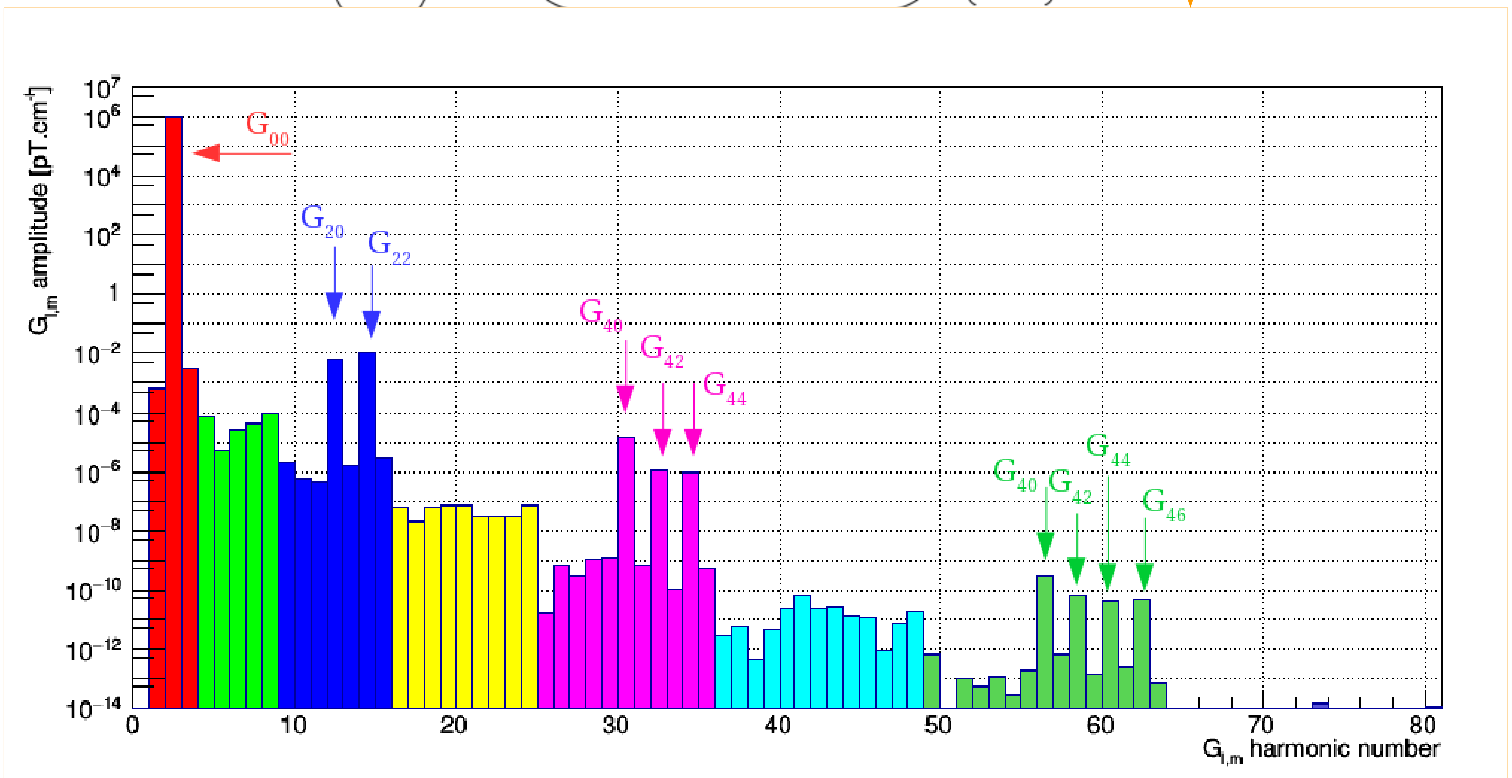
l	m	H_x	H_y	H_z	n°
0	-1	0	1	0	1
0	0	0	0	1	2
0	1	1	0	0	3
1	-2	y	x	0	4
1	-1	0	z	y	5
1	0	-x/2	-y/2	z	6
1	1	z	0	x	7
1	2	x	-y	0	8
2	-3	2xy	$x^2 - y^2$	0	9

Single Value Decomposition method (SVD)

B = H . G

$$
\begin{pmatrix} B_x(0) \\ B_y(0) \\ B_z(0) \\ B_x(1) \\ B_y(1) \\ B_z(1) \\ \dots \\ B_x(n) \\ B_y(n) \\ B_z(n) \end{pmatrix}
=
\begin{pmatrix}
H_{x01}(0) & H_{x00}(0) & H_{x01}(0) & \dots & H_{x78}(0) \\
H_{y01}(0) & H_{y00}(0) & H_{y01}(0) & \dots & H_{y78}(0) \\
H_{z01}(0) & H_{z00}(0) & H_{z01}(0) & \dots & H_{z78}(0) \\
H_{x01}(1) & H_{x00}(1) & H_{x01}(1) & \dots & H_{x78}(1) \\
H_{y01}(1) & H_{y00}(1) & H_{y01}(1) & \dots & H_{y78}(1) \\
H_{z01}(1) & H_{z00}(1) & H_{z01}(1) & \dots & H_{z78}(1) \\
\dots & \dots & \dots & \dots & \dots \\
H_{x01}(n) & H_{x00}(n) & H_{x01}(n) & \dots & H_{x78}(n) \\
H_{y01}(n) & H_{y00}(n) & H_{y01}(n) & \dots & H_{y78}(n) \\
H_{z01}(n) & H_{z00}(n) & H_{z01}(n) & \dots & H_{z78}(n)
\end{pmatrix}
\begin{pmatrix} G_{01} \\ G_{00} \\ G_{01} \\ G_{12} \\ G_{11} \\ G_{10} \\ \dots \\ G_{76} \\ G_{77} \\ G_{78} \end{pmatrix}
$$

Computed Gradients



Harmonic Decomposition of B_0 coil

→ Magnetic field is decomposed on a harmonic polynomial basis

$$\mathbf{B}(\mathbf{r}) = \Sigma_{l,m} G_{l,m}\ \mathbf{H}_{l,m}(\mathbf{r})$$

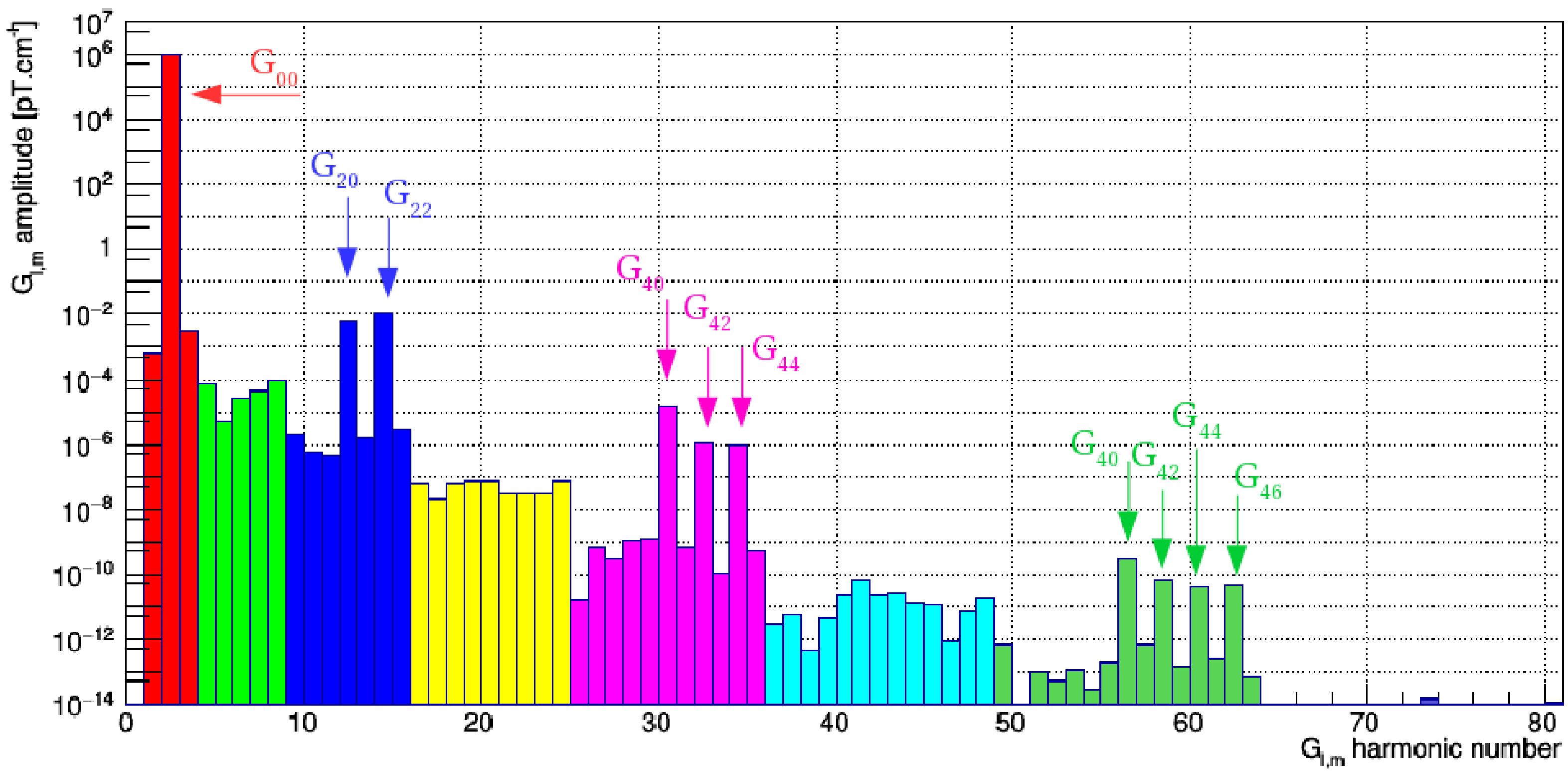
		Field Components		
		Bx(x,y,z)	By(x,y,z)	Bz(x,y,z)
Symmetries	X → -X	- Bx(-x,y,z)	By(-x,y,z)	Bz(-x,y,z)
	Y → -Y	Bx(x,-y,z)	- By(x,-y,z)	Bz(x,-y,z)
	Z → -Z	- Bx(x,y,-z)	- By(x,y,-z)	Bz(x,y,-z)

→ Terms who don't respect thoses symmetries are **forbidden**

→ Theirs assiocated $G_{l,m}$ must be equal to 0 $pT.cm^{-l}$

Harmonic Decomposition of B_0 coil

Performed with 10 000 points, volume of interest of 1 m³ ($x,y,z \in [-0.5 ; 0.5]$ m)

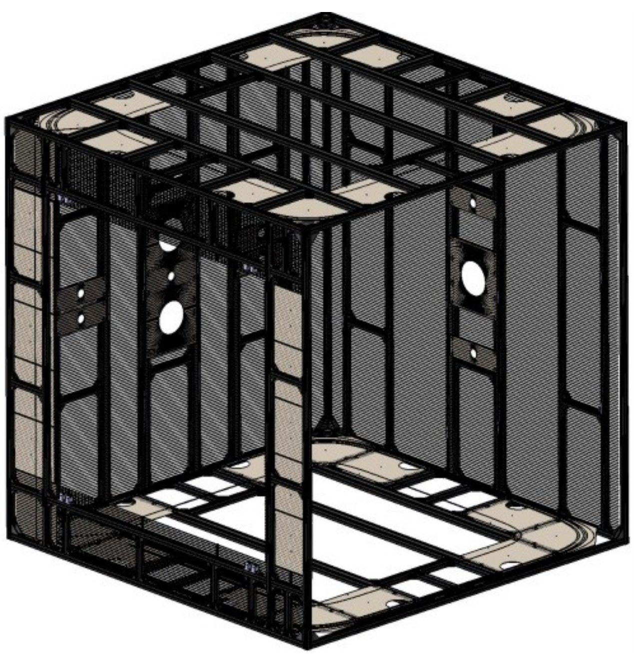


Forbidden terms / Allowed terms : at least 10^{-3}

Forbidden terms → finite discretisation of space

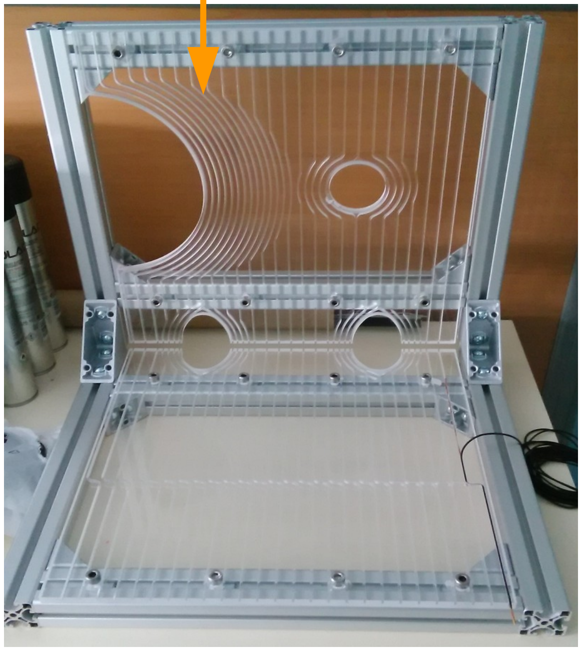
Mechanical solutions – n2EDM BenCo

Plan to use grooved plexiglas plates :
- groove path = B_0 coil design
- wires stuck in the grooves



Without door and right panel

Hole by pass



Plexiglass prototype

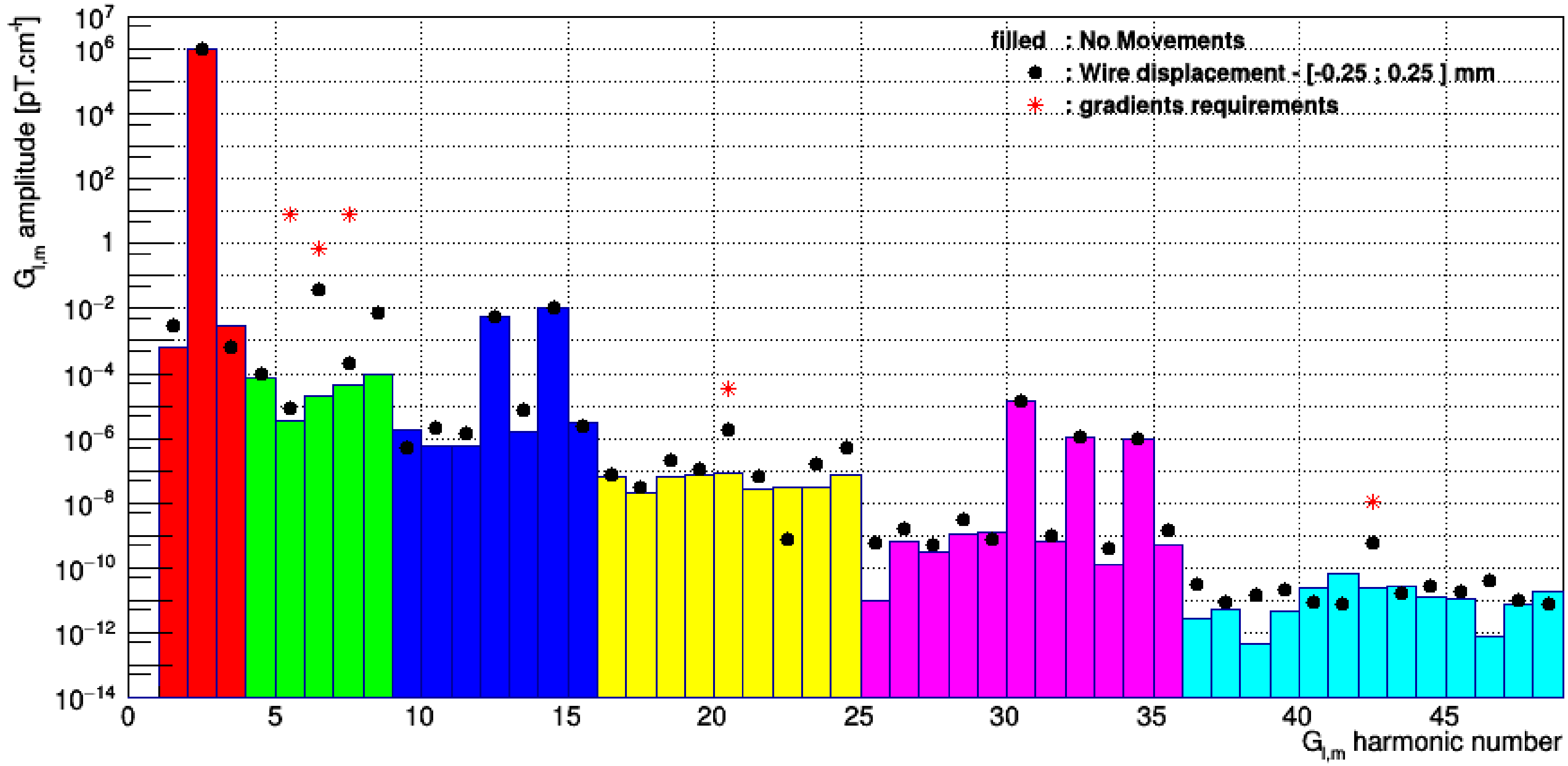
A wire oscillating inside a groove on the plexiglass prototype.

→ Influence of the mechanical imperfections ?

Influence of the wire positionning

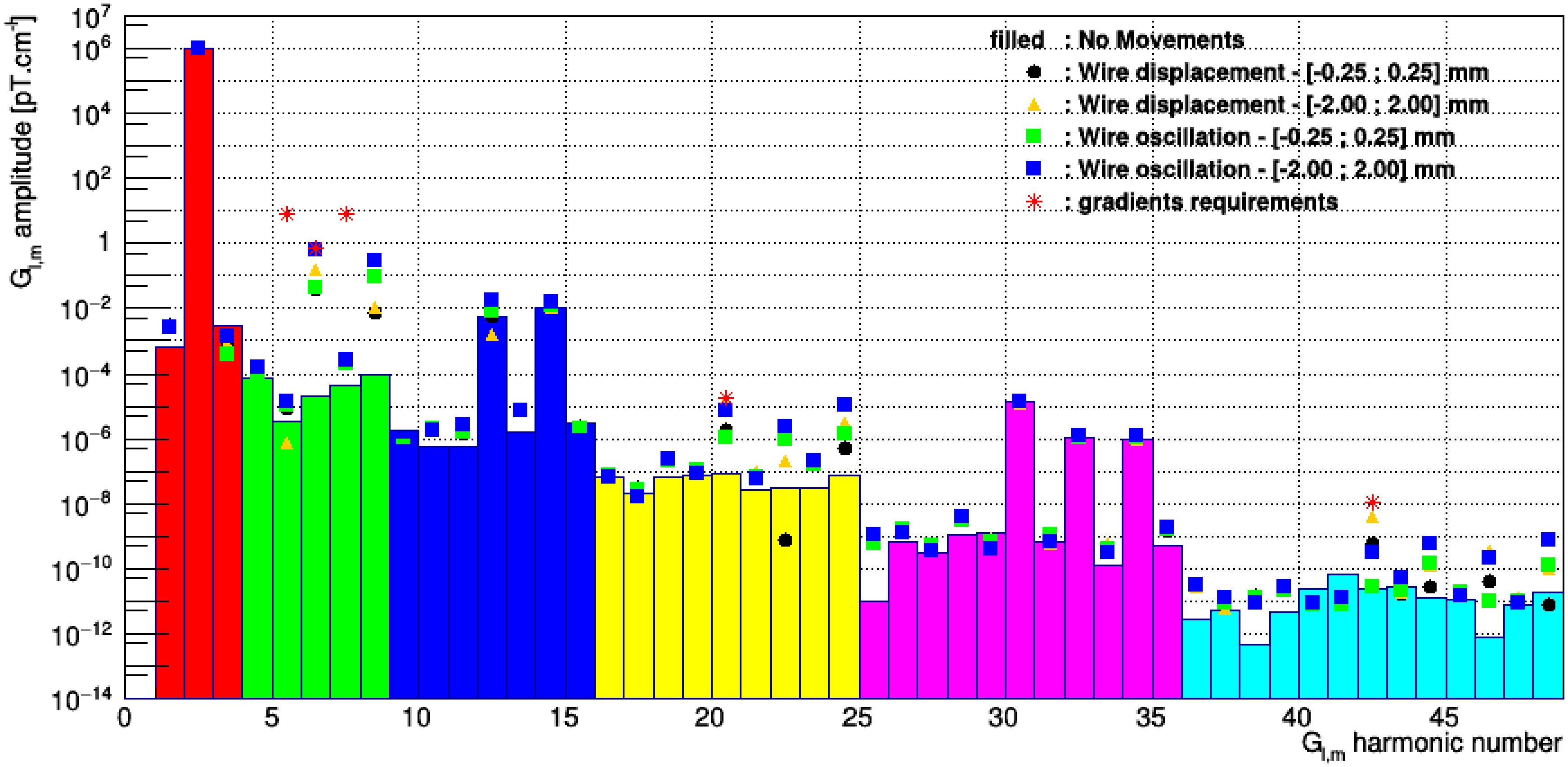
Two different type of movements were studied :
- Random wire displacements ;
- Random wire oscillations.

→ Z-symmetry broken : $G_{1,0}$, $G_{1,2}$, $G_{3,0}$, $G_{3,2}$, $G_{3,4}$, $G_{5,0}$ … gradients allowed



Influence of the wire positionning

→ Z-symmetry broken : $G_{1,0}$, $G_{1,2}$, $G_{3,0}$, $G_{3,2}$, $G_{3,4}$, $G_{5,0}$ … gradients allowed



→ Gradients under requirements even for unrealistic wires movements

Mechanical Imperfections

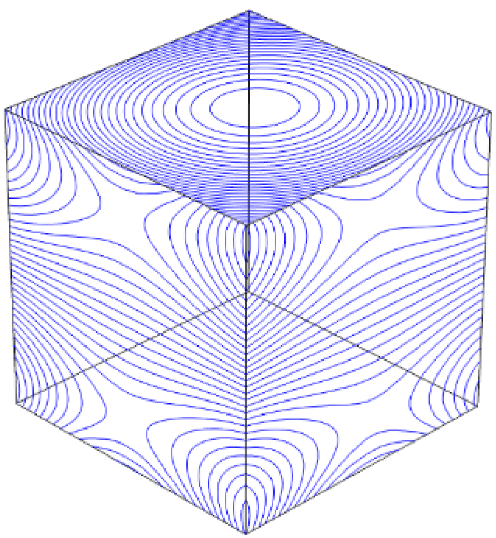
Type of imperfection :	Impact on the magnetic field :
Individual wires movement $\Delta z = 2$ mm	Requirements fulfilled
Modification of shield μ_r on top/bottom (at most ± 20%)	Requirements fulfilled
Vertical precession chamber displacement $\Delta z = 10$ cm	Requirements fulfilled
Horizontal B0 coil displacement (along x, y axis) with respect to the shield $\Delta z = 5$ mm	Requirements fulfilled
Vertical B0 coil displacement (along z axis) with respect to the shield	**$G_{1,0}$ out of range for $\Delta z = 0.25$ mm $G_{1,0}$ & $G_{3,0}$ out of range for $\Delta z = 1$ mm**

→ Conclusion : the vertical positionning have to be very precise …
but very hard at the level of 0.25 mm,
→ need for correcting coils

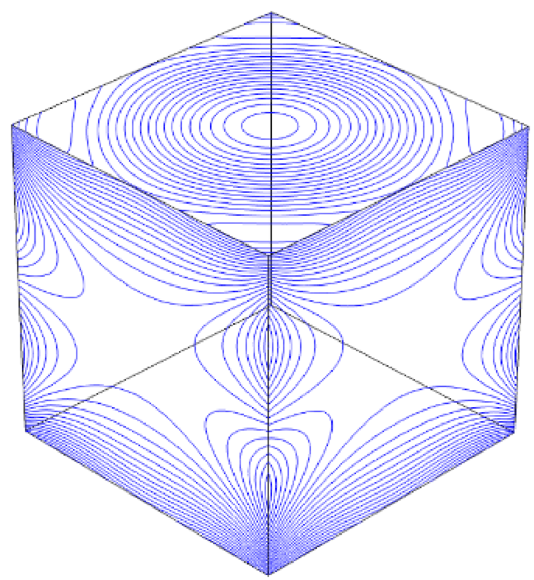
Correcting coils

Several possibilities : Dedicated coil and/or set of coil

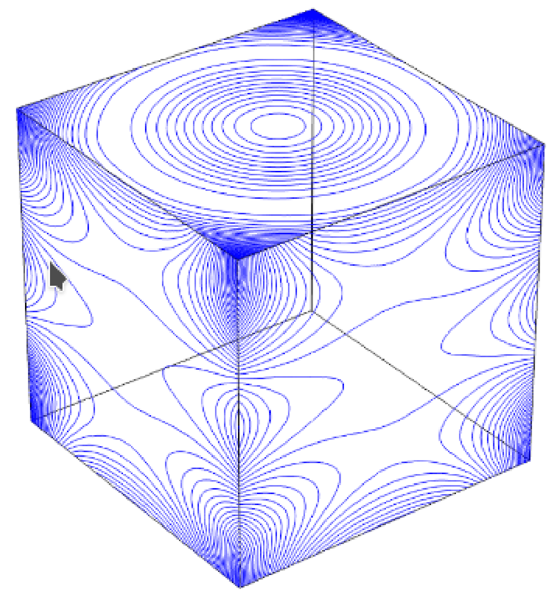
- Dedicated correcting coil[1] for every important gradient ($G_{1,0}$, $G_{3,0}$, etc.):
  - Design from laplace equation & bondaries conditions
  - Shape of such coils can be rather complicated



Single layer $G_{3,0}$ coil



Single layer $G_{5,0}$ coil



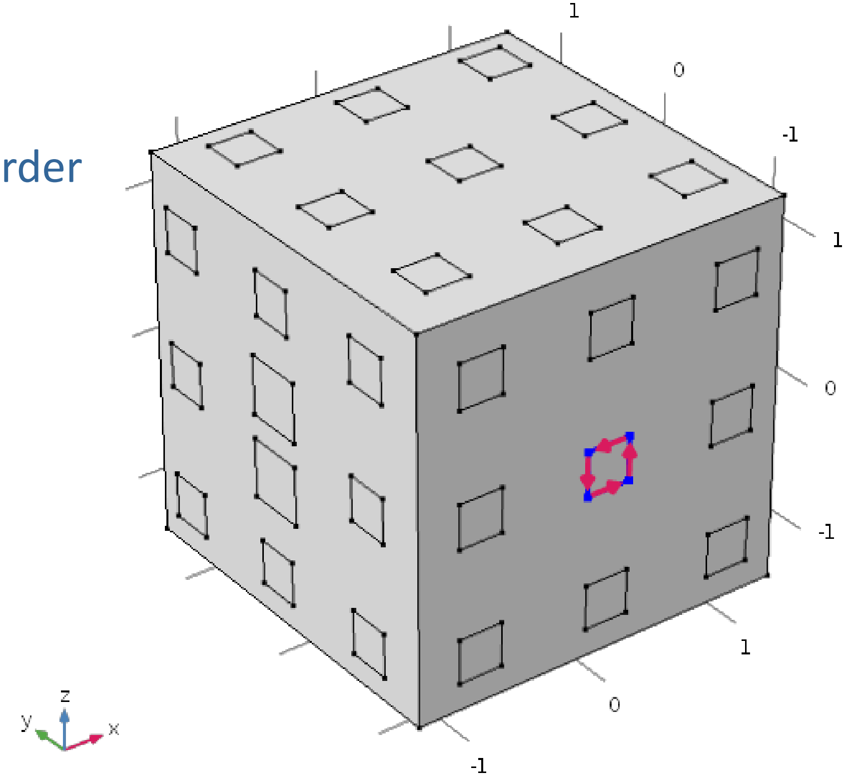
Single layer $G_{6,0}$ coil

[1] Magnetic fields for the SNS neutron EDM experiment, Chris Crawford, PSI UCN Seminar, 2012-06-28

Correcting coils

Several possibilities : Dedicated coil and/or set of coil

- Set of 56 correcting coil able to correct up to the 6th order



$$\begin{pmatrix} G_{0,-1} \\ G_{0,0} \\ G_{0,1} \\ G_{1,-2} \\ \vdots \\ G_{7,8} \end{pmatrix} = \begin{pmatrix} G^{TC1}_{0,-1} & G^{TC2}_{0,-1} & \cdots & G^{TC56}_{0,-1} \\ G^{TC1}_{0,0} & G^{TC2}_{0,0} & \cdots & G^{TC56}_{0,0} \\ G^{TC1}_{0,1} & G^{TC2}_{0,1} & \cdots & G^{TC56}_{0,1} \\ G^{TC1}_{1,-2} & G^{TC2}_{1,-2} & \cdots & G^{TC56}_{1,-2} \\ \vdots & \vdots & \vdots & \vdots \\ G^{TC1}_{7,8} & G^{TC2}_{7,8} & \cdots & G^{TC56}_{7,8} \end{pmatrix} \begin{pmatrix} I^{TC1} \\ I^{TC2} \\ \vdots \\ I^{TC56} \end{pmatrix}$$

Gradients to correct

Gradients created
By each Trim Coil
With a given current

→ List of coil currents

WORK ON GOING

Conclusion

→ « Perfect Coil » fulfilled the requirements

→ Wire displacements and oscillations
→ x & y global displacement of the coil
→ Shield relative permeability
→ Displacement of the precession chamber

} Requirements still fulfilled

→ But : Global vertical displacement of the B_0 coil

→ $G_{1,0}$ out of range with $\Delta z = 0.25$ mm

→ Solving the problem by :

- Find the best position of B_0 with respect to the shield

→ Field map measurements

Hovever all imperfections have not been simulated, which may produce out of range gradients

→ A set of correcting coils is required (work on going)

Thank you for your attention !

Annex

Robustness of the simulation

- COMSOL influence :

  - Meshing Size → Low impact on the harmonic decomposition
  - Interpolation order → 2nd order precise enough

- SVD influence :

  - SVD numerical background → Forbidden/Allowed ~ 10^{-9}
  - Density of points→ Optimal combination : 10000 pts, V = 1 m^3

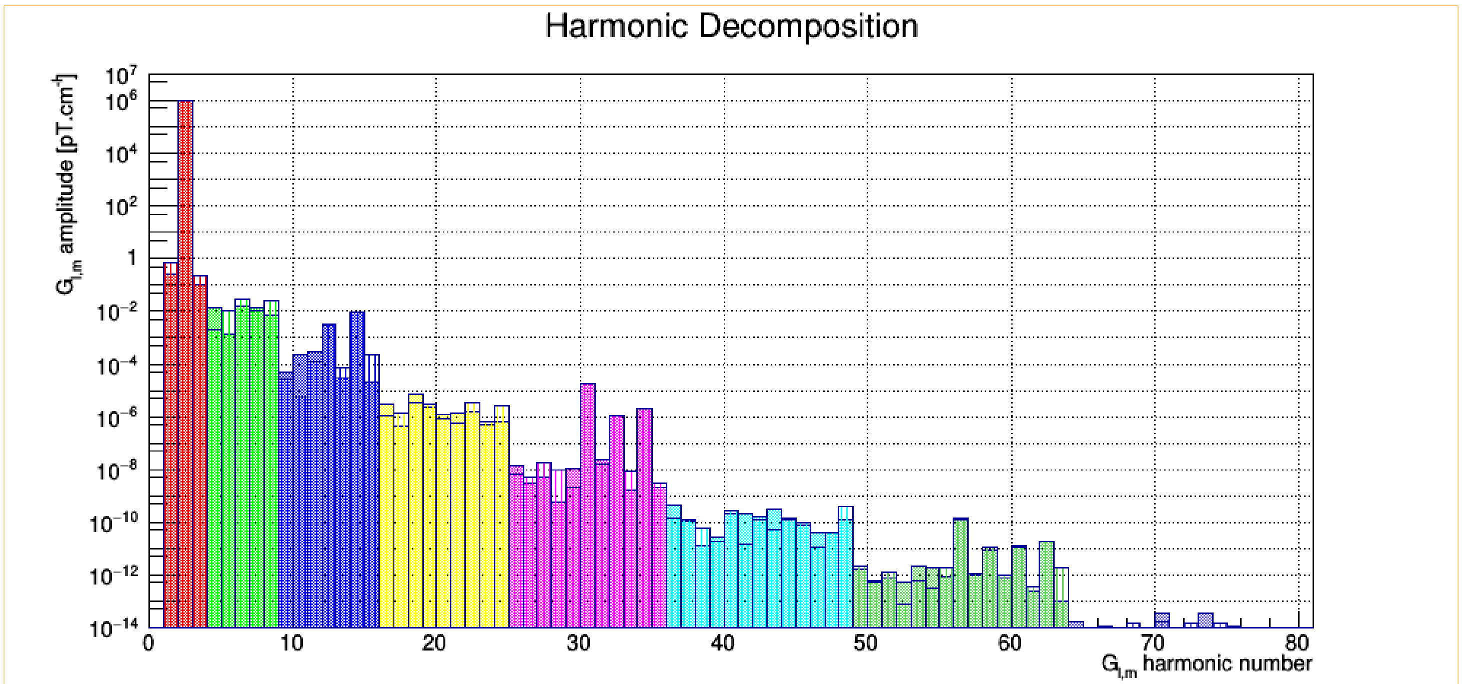
Allowed gradients are not influenced by the simulation parameters.
Only forbidden gradients (numerical noise) are moderatly changing

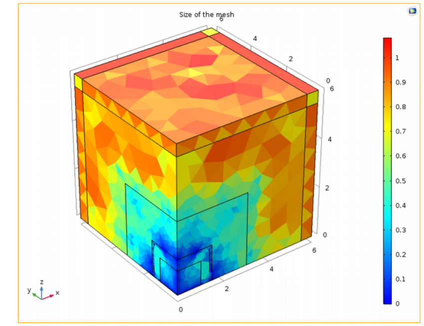
The simulation is robust

COMSOL meshing size

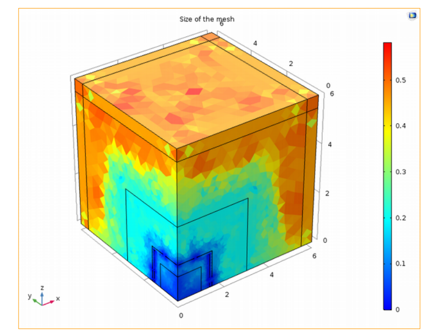
Normal mesh : Tetrahedrals and triangular elements

Max length of elements in 1 m^3 < 20 cm

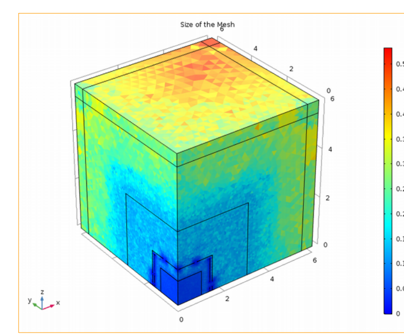




Coarse mesh



Used mesh



Extremely fine mesh

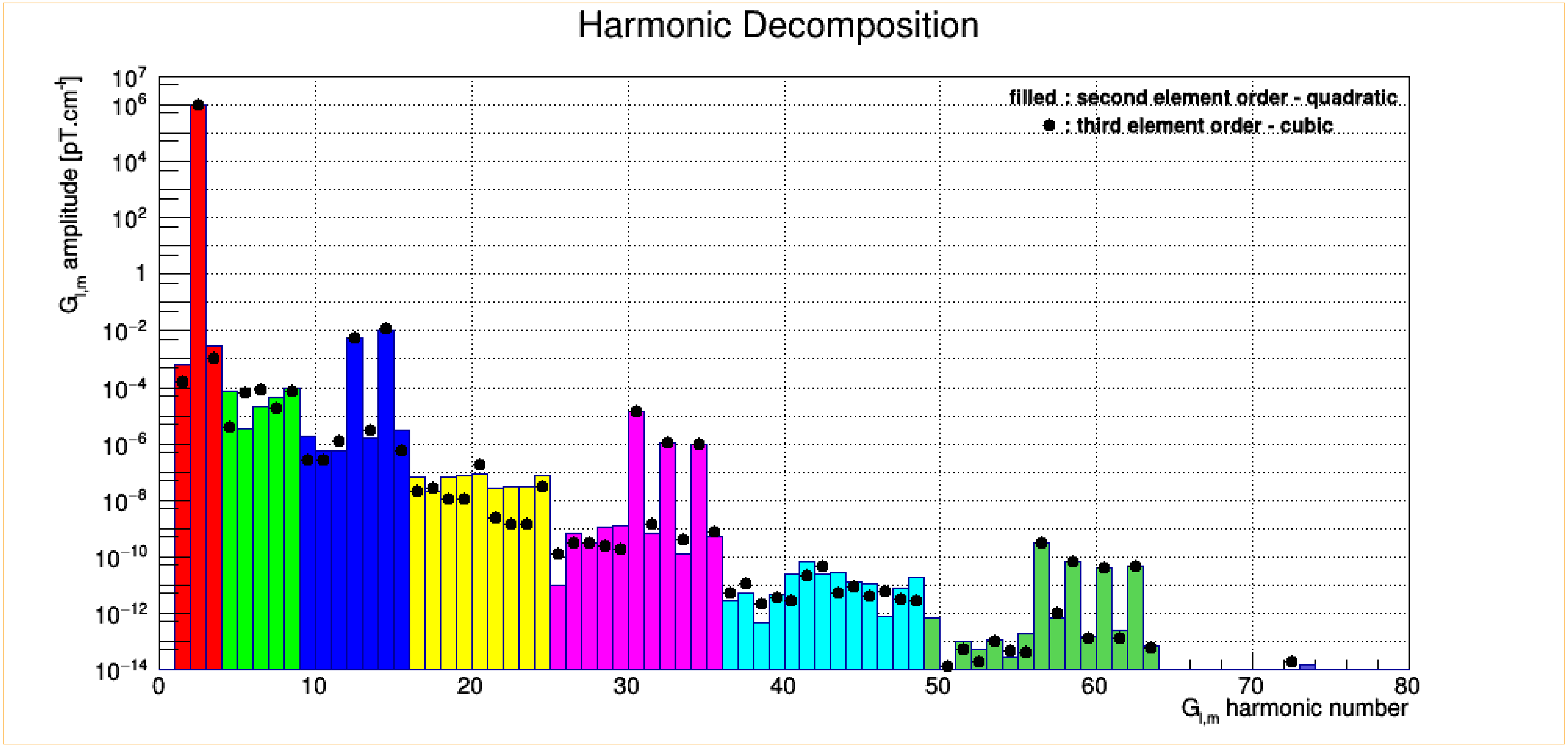
No changes on allowed terms

Low changes for numerical background

→ Low impact of COMSOL meshing size

Influence of the element order

Element order = order of interpolation of the magnetic field between two nodes of the element



→ Gain at most factor 10, but calculation loads x5

└→ keep on working with second element order.

Precision of the harmonic decomposition

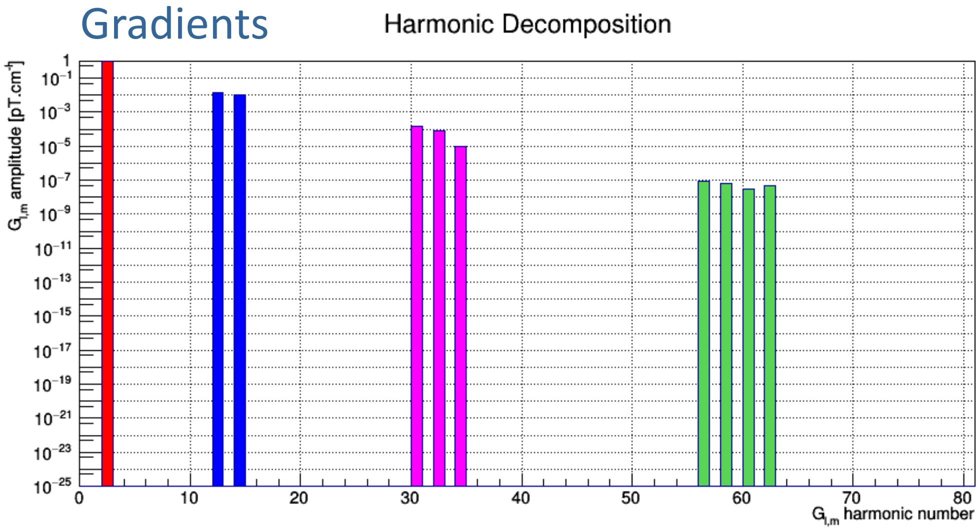
1	0
2	10^6
3	0
…	
…	
80	0

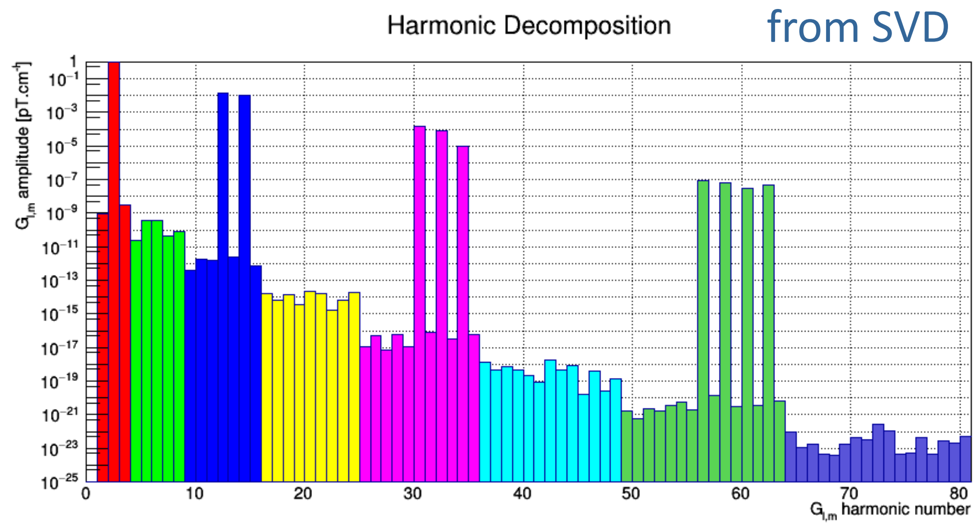
Known Gradients

Field Reconstruction → Field Map → Field Decomposition →

1	10^{-9}
2	10^6
3	10^{-9}
…	
…	
80	10^{-23}

Gradients from SVD



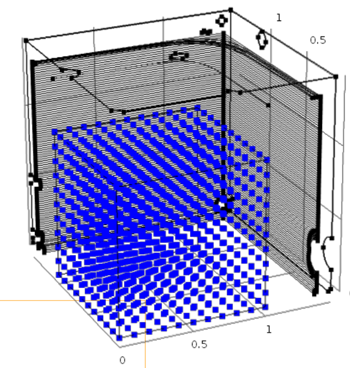


→ Allowed terms well reproduced

→ Forbidden terms set to 0 → Harmonic Decomposition background

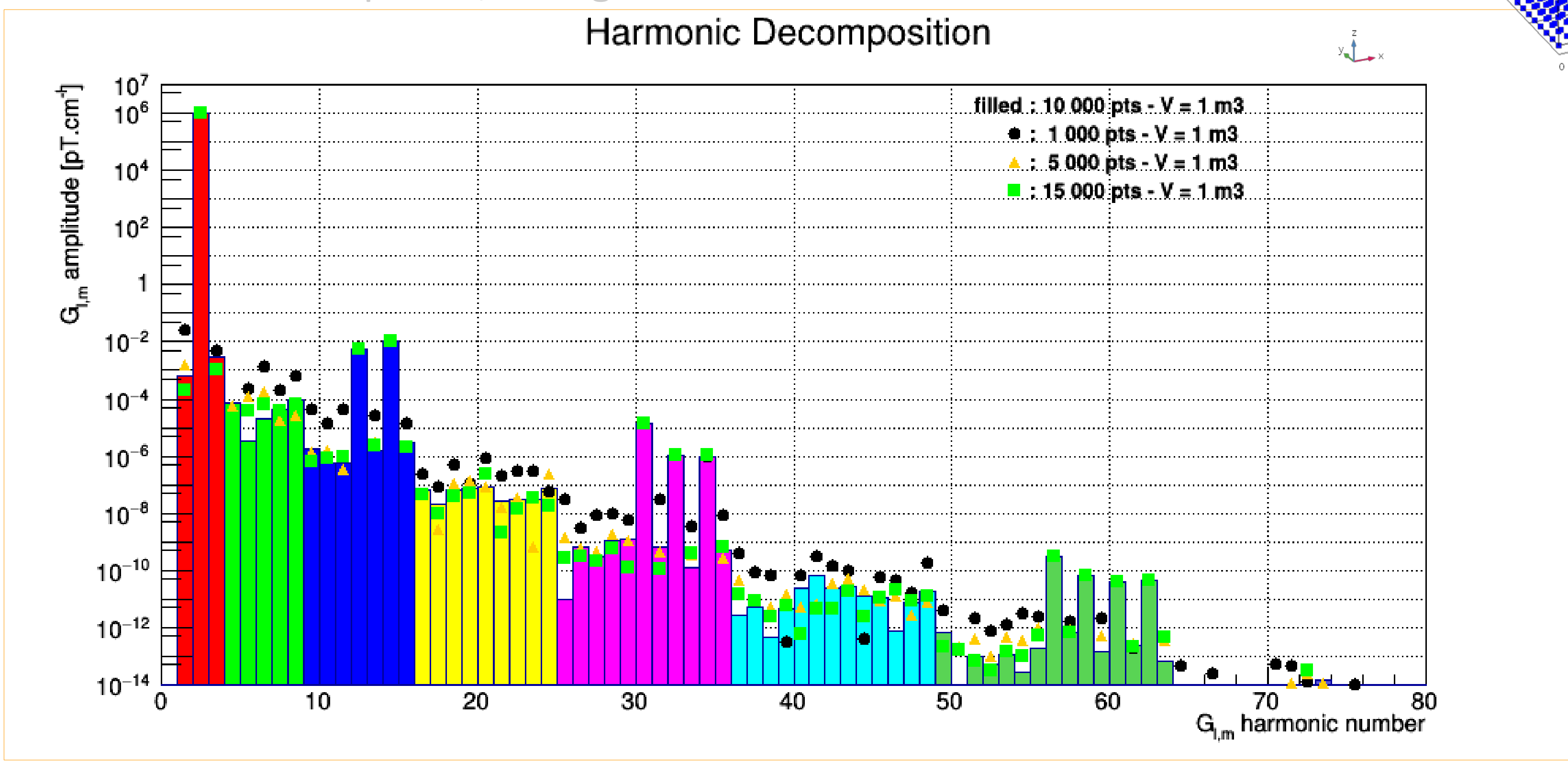
└ Background/Allowed at least 10^{-9} (for 10 000 points and V = $1m^3$)

Influence of the density of points for SVD



Two ways of changing the points density :

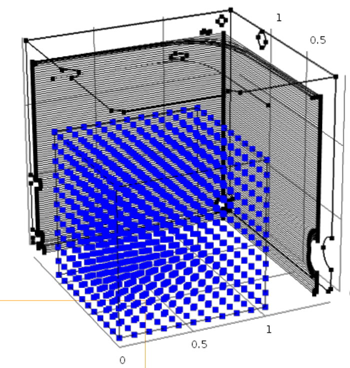
- Same volume of data, change the number of points
- Same number of points, change the volume of data



→ 1000 to 10 000 pts : factor 10
→ 10 000 to 15 000 pts : about the same
→ over 15 000 pts : out of calculations

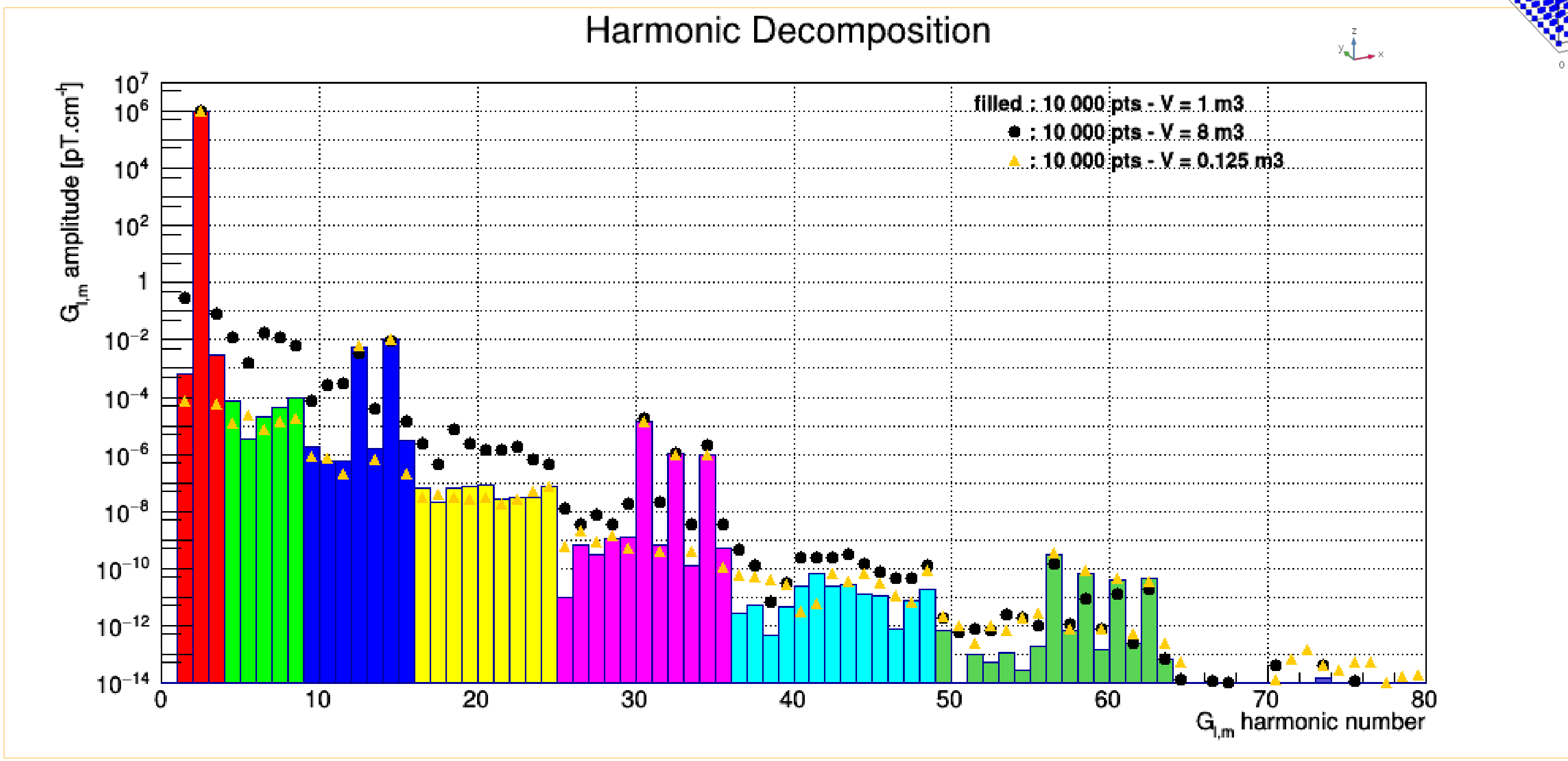
10 000 points chosen for the SVD

Influence of the density of points for SVD



Two ways of changing the points density :

- Same volume of data, change the number of points
- Same number of points, change the volume of data



→ 8 m³ to 1 m³ : factor ~100 before l= 3 , factor ~10 after

→ 1 m³ to 0.125 m³ : factor ~10 on $G_{0,-1}$ & $G_{0,1}$,getting worse after l=6

V = 1 m³ chosen

Influence of the wire positionning

Two different type of movements were studied :

- Random wire displacements

Side wires	$z_{wires} = z_{init} + z_{displacement}$
Lamé curves	$x_{lame} = (a + x_{displacement}).\cos^n(\theta)$ $y_{lame} = (a + y_{displacement}).\sin^n(\theta)$

With $\{x,y,z\}_{displacement} \in [-0.25 ; 0.25]$ mm (realistic)

Or $\in [-2.00 ; 2.00]$ mm (extreme case)

- Random wire oscillations

Side wires	$z_{wires} = z_{init} + A.\cos(\nu_z.\theta + \phi)$
Lamé curves	$x_{wires} = a.\cos^n(\theta) + A.\cos(\nu_x.\theta + \phi)$ $y_{wires} = a.\sin^n(\theta) + A.\cos(\nu_y.\theta + \phi)$

With $\{\nu_x,\nu_y,\nu_z\} \in [0 ; 366]\ m^{-1}$ (test on prototype : $\nu_z = 27\ m^{-1}$)

$\varphi \in [0 ; 2\pi]$ rad

$A \in [-0.25 ; 0.25]$ mm (realistic)

Or $\in [-2.00 ; 2.00]$ mm (extreme case)

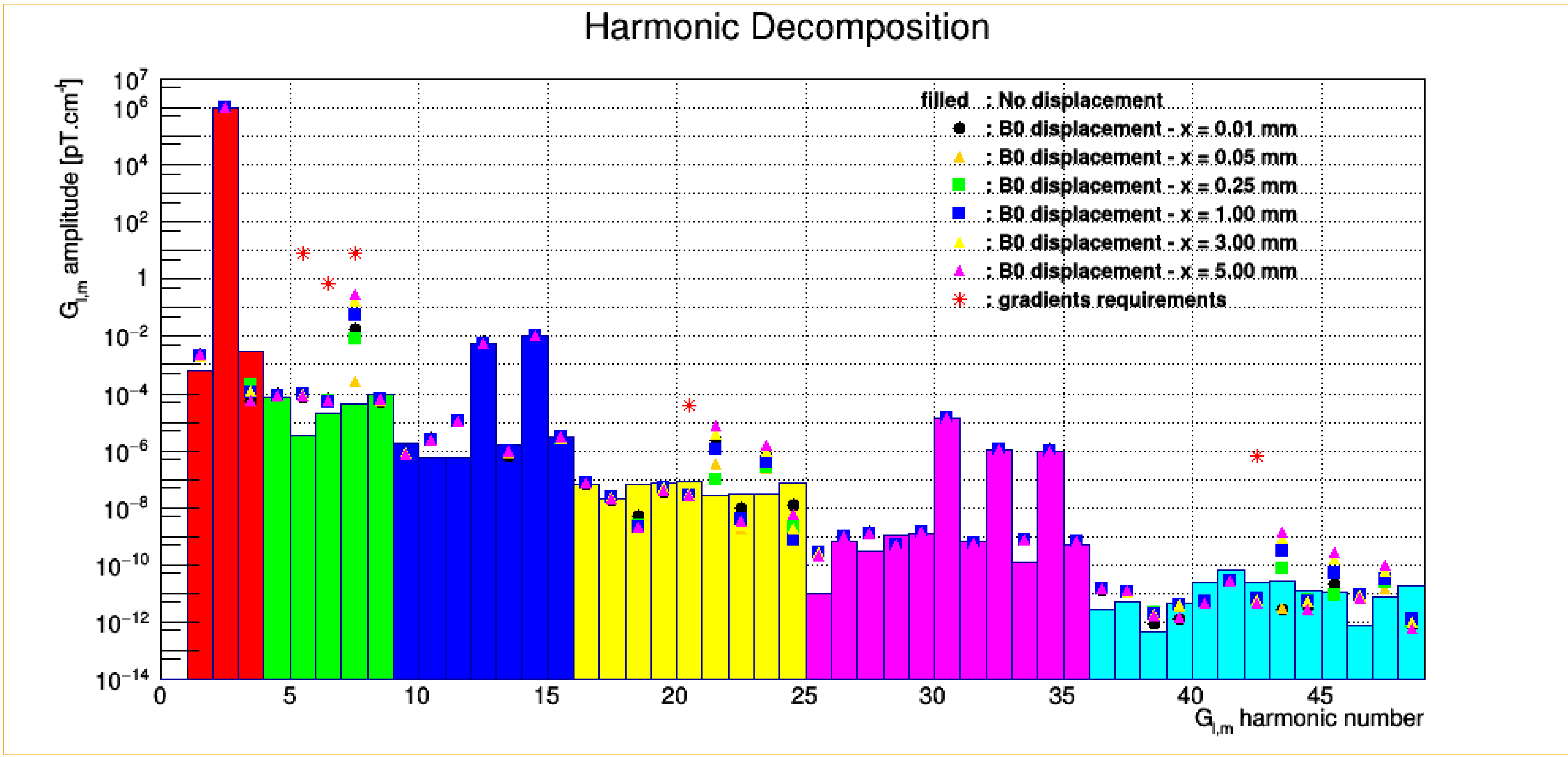
Main gradients from wire positionning

Wire movements	Gradient Requirements	w/o movements	$W_{disp} \in$ [-0.25 ; 0.25] mm	$W_{disp} \in$ [-2.00 ; 2.00] mm	$W_{osc} \in$ [-0.25 ; 0.25] mm	$W_{osc} \in$ [-2.00 ; 2.00] mm
B_{center} [pT]	**= 1.10^6**	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$	$0.9999.10^6$
$G_{0,0}$ [pT]	**—**	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$
$G_{1,-1}$ [pT.cm^{-1}]	**< 8**	$3.36.10^{-6}$	$-8.87.10^{-6}$	$-7.61.10^{-7}$	$-1.07.10^{-5}$	$-1.37.10^{-7}$
$G_{1,0}$ [pT.cm^{-1}]	**< 0,7**	$-2.00.10^{-5}$	$-3.37.10^{-2}$	$-1.45.10^{-1}$	$-4.23.10^{-2}$	$-6.58.10^{-1}$
$G_{1,1}$ [pT.cm^{-1}]	**< 8**	$-4.31.10^{-5}$	$-2.14.10^{-4}$	$2,11.10^{-4}$	$2.10.10^{-4}$	$2.11.10^{-4}$
$G_{3,0}$ [pT.cm^{-3}]	**< $3.3.10^{-5}$**	$7.99.10^{-8}$	$1.89.10^{-6}$	$1,64.10^{-5}$	$1.04.10^{-6}$	$-7.18.10^{-6}$
$G_{5,0}$ [pT.cm^{-5}]	**< $1.1.10^{-8}$**	$2.39.10^{-11}$	$5.80.10^{-10}$	$3.81.10^{-9}$	$2.77.10^{-11}$	$3.14.10^{-10}$

Forbidden Gradients

Displacement of the B_0 coil with respect to the shield

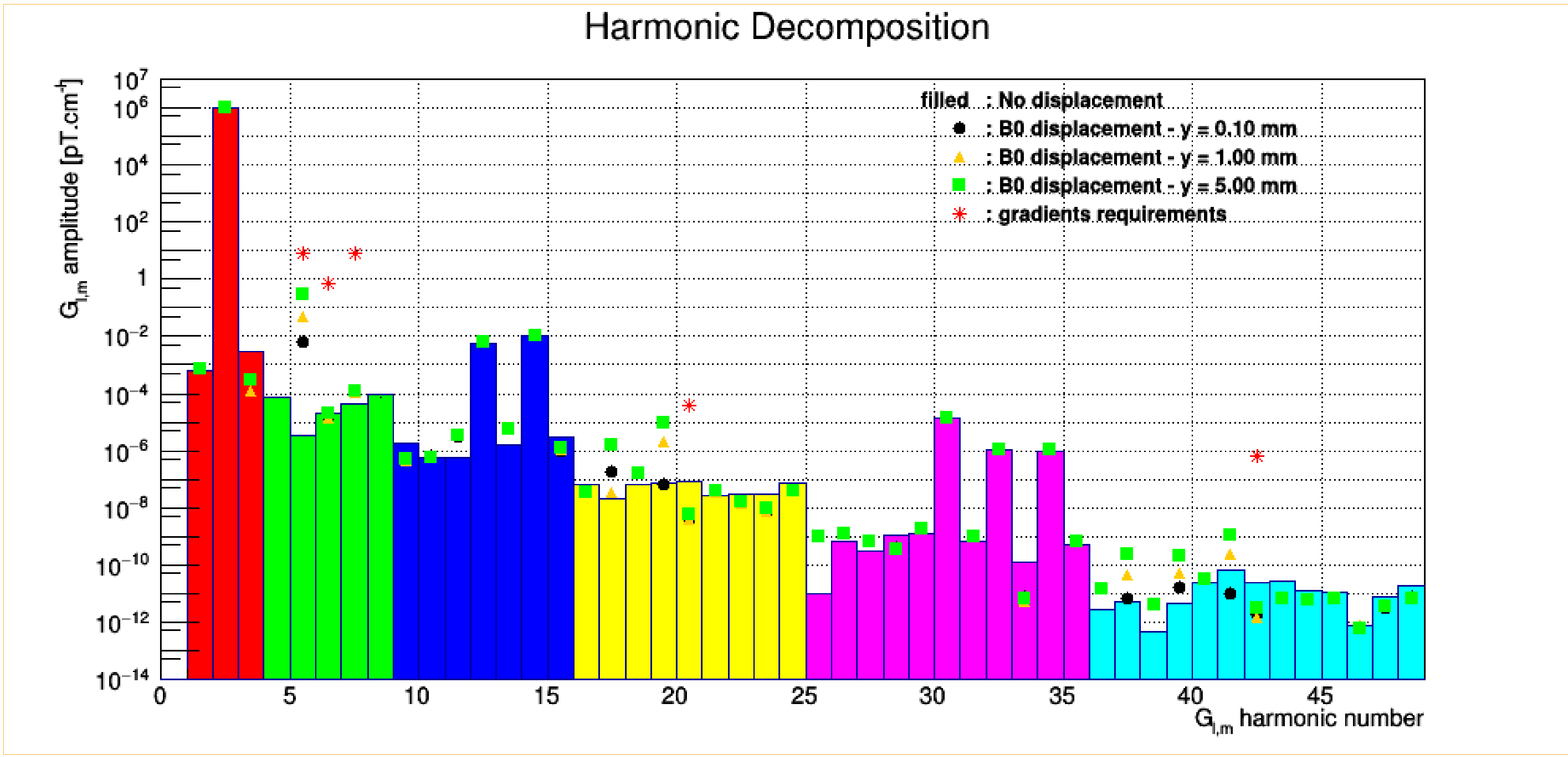
Displacemements of the B_0 coil along x axis :



→ The requirements are fulfilled even a x = 5 mm displacement

Displacement of the B_0 coil with respect to the shield

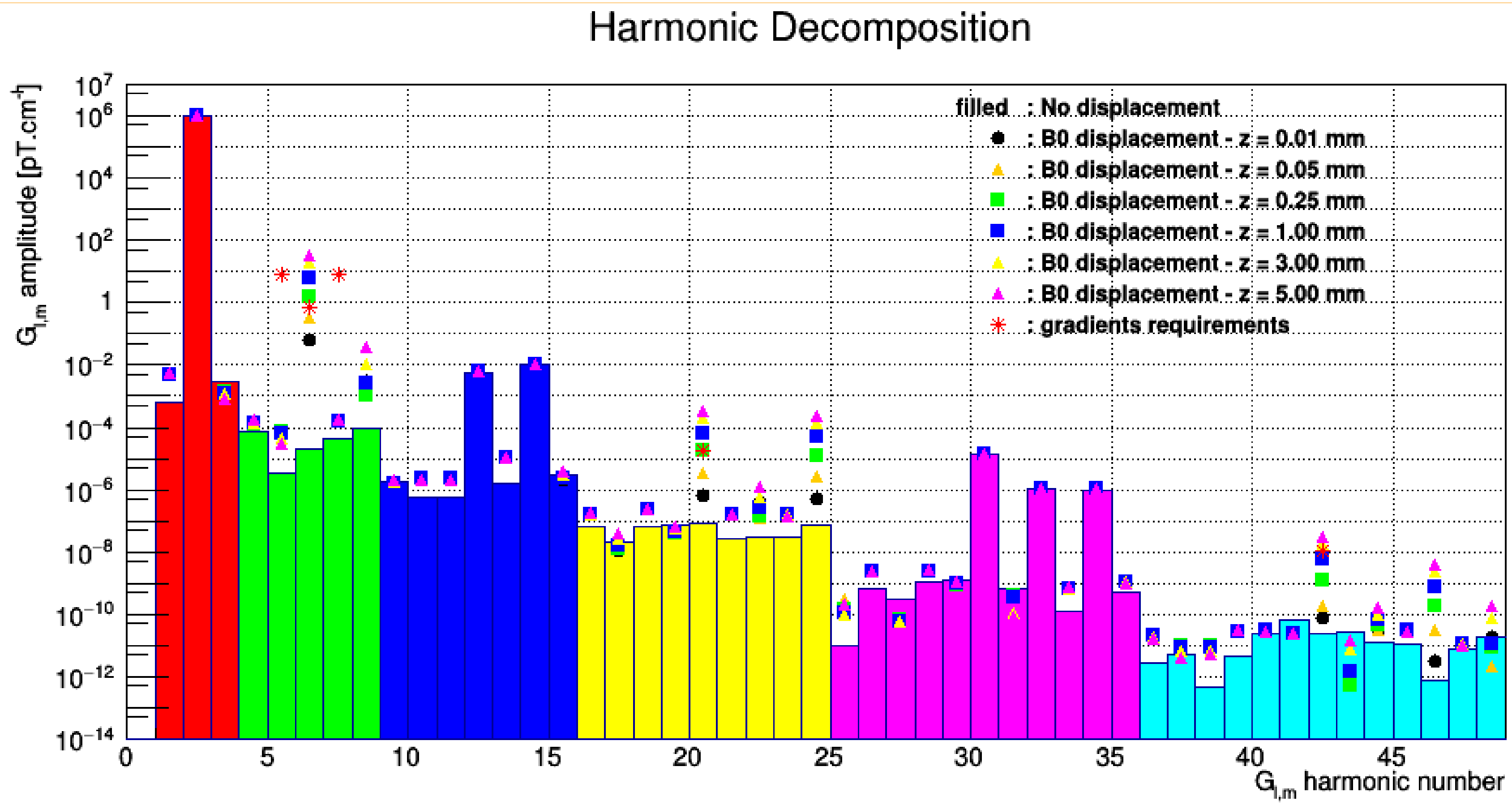
Displacemements of the B_0 coil along y axis :



→ The requirements are fulfilled even a y = 5 mm displacement

Displacement of the B_0 coil with respect to the shield

Displacemements of the B_0 coil along z axis :



→ $G_{1,0}$ requirement excedeed after z = 0.25 mm displacement

→ $G_{1,0}$ & $G_{3,0}$ requirements excedeed after z = 1 mm displacement

Displacement of the B_0 coil with respect to the shield

Displacemements of the B_0 coil along x, y and z axis :

→ X-symmetry broken : $G_{1,1}$, $G_{3,1}$, $G_{3,3}$ ... gradients allowed

→ Y-symmetry broken : $G_{1,-1}$, $G_{3,-3}$, $G_{3,-1}$ ... gradients allowed

→ Z-symmetry broken : $G_{1,0}$, $G_{1,2}$, $G_{3,0}$, $G_{3,2}$, $G_{3,4}$, $G_{5,0}$ ... gradients allowed

B_0 movements	Gradient Requirements	w/o movements	z_d = 0.25 mm	z_d = 1 mm	z_d = 5 mm	x_d = 5 mm	y_d = 5 mm
B_{center} [pT]	**= 1.10^6**	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$	$1.0000.10^6$
$G_{0,0}$ [pT]	—	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$	$1.00.10^6$
$G_{1,-1}$ [pT.cm^{-1}]	**< 8**	$3.36.10^{-6}$	$-1.07.10^{-5}$	$-6.26.10^{-5}$	$-2.94.10^{-5}$	$-8.55.10^{-5}$	$2.87.10^{-1}$
$G_{1,0}$ [pT.cm^{-1}]	**< 0,7**	$-2.00.10^{-5}$	1.60	6.43	32.5	$-5.93.10^{-5}$	$2.16.10^{-5}$
$G_{1,1}$ [pT.cm^{-1}]	**< 8**	$-4.31.10^{-5}$	$-2.10.10^{-4}$	$1.60.10^{-4}$	$1.78.10^{-4}$	$2.99.10^{-1}$	$1.26.10^{-4}$
$G_{3,0}$ [pT.cm^{-3}]	**< $3.3.10^{-5}$**	$7.99.10^{-8}$	$1.69.10^{-5}$	$-6.78.10^{-5}$	$3.38.10^{-4}$	$-2.83.10^{-8}$	$-5.78.10^{-9}$
$G_{5,0}$ [pT.cm^{-5}]	**< $1.1.10^{-8}$**	$2.39.10^{-11}$	$-1.30.10^{-9}$	$-5.66.10^{-9}$	$-2.87.10^{-8}$	$4.76.10^{-12}$	$3.20.10^{-12}$

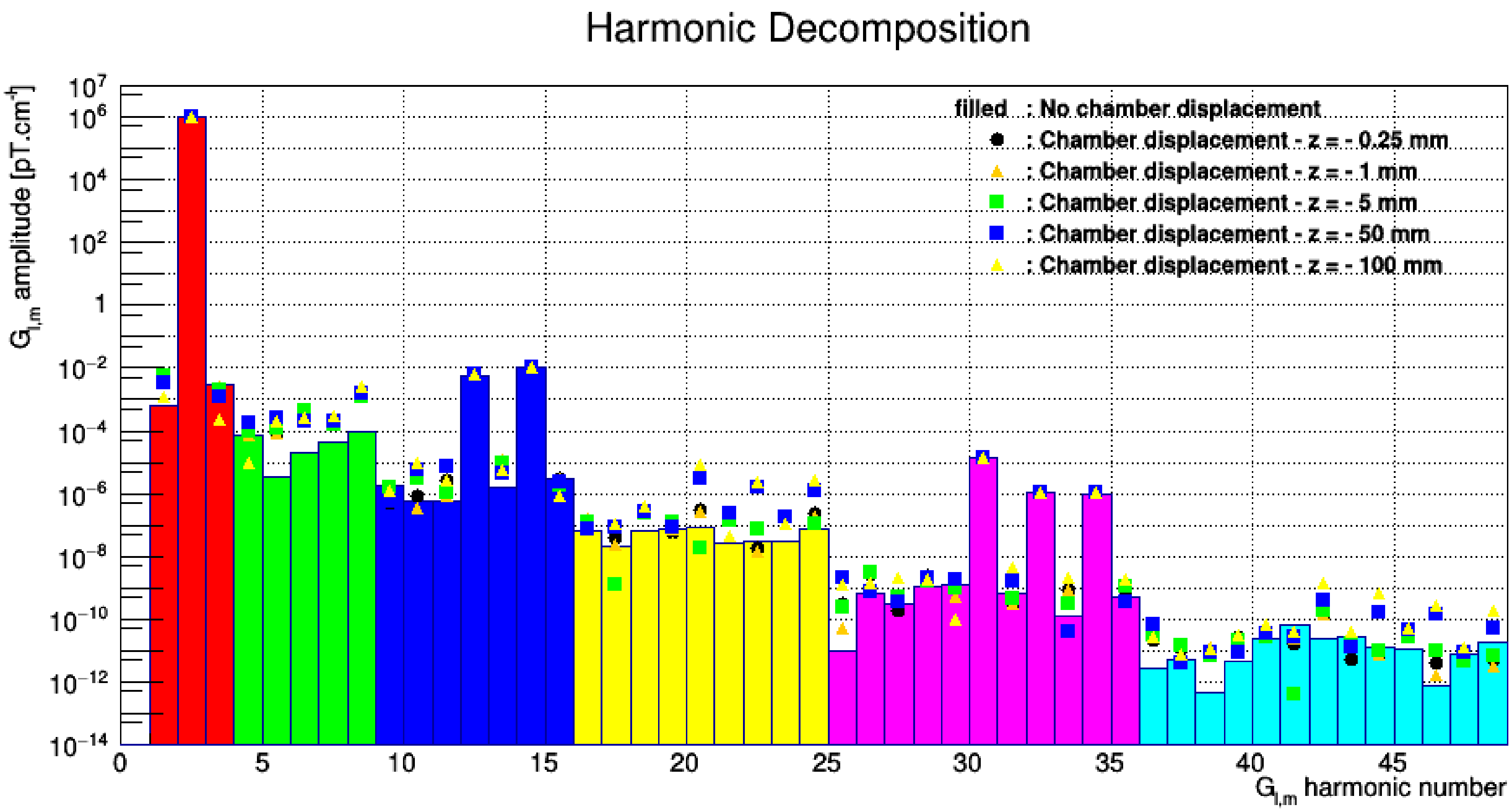
Forbidden Gradients

Gradient above requirement

→ large x & y displacement → gradients OK

→ z displacement of 0.25 mm → $G_{1,0}$ requirement exceeded

Displacement of the precession chamber with respect to the B_0 coil and the shield



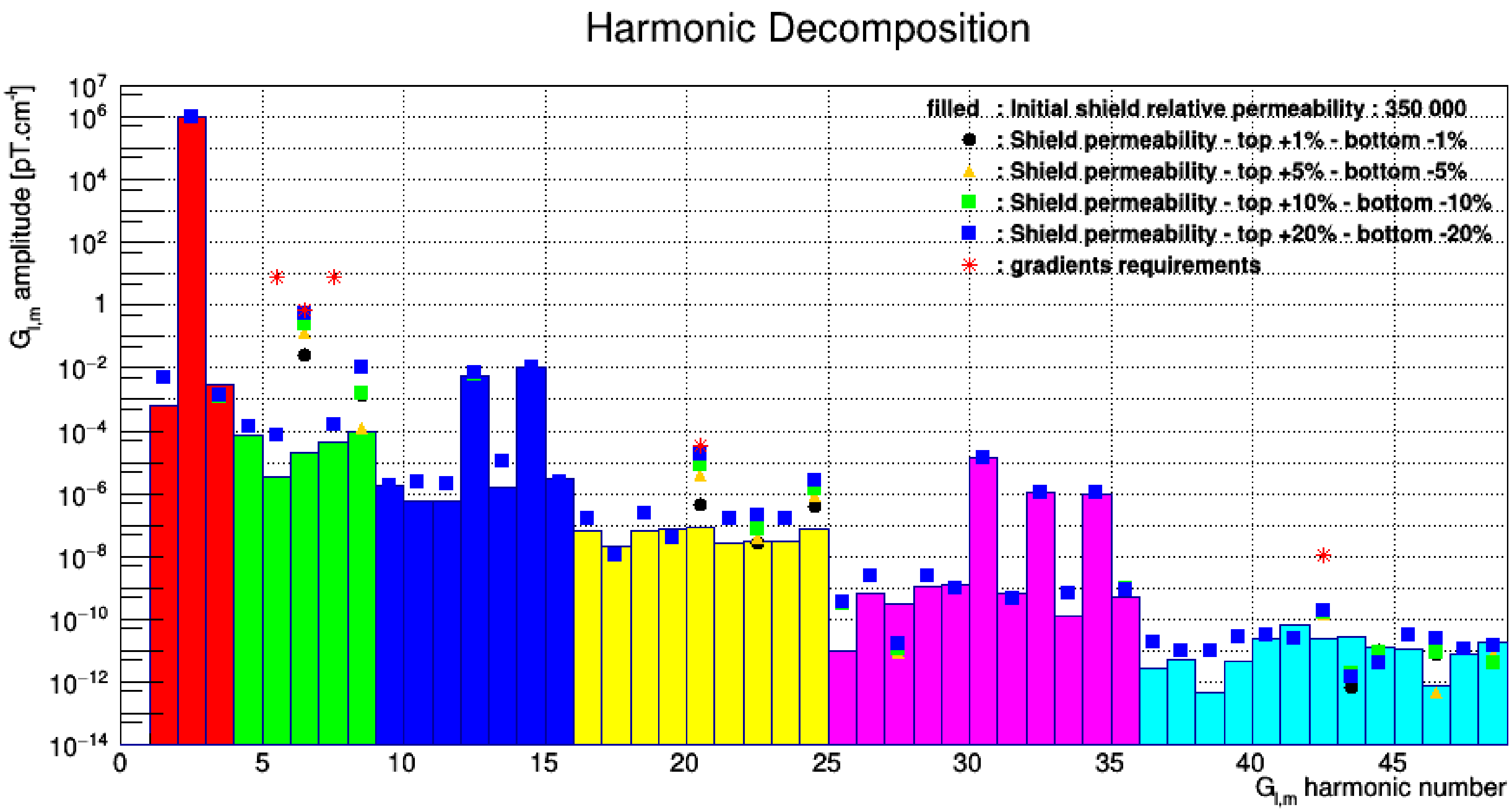
→ Weak increase of the background (max ~ factor 15)

→ Weak emergence of Z-symmetry breaks gradients for big displacements (5, 10 cm)

↳ Good uniformity on the chambers area

Influence of the shield relative permeability

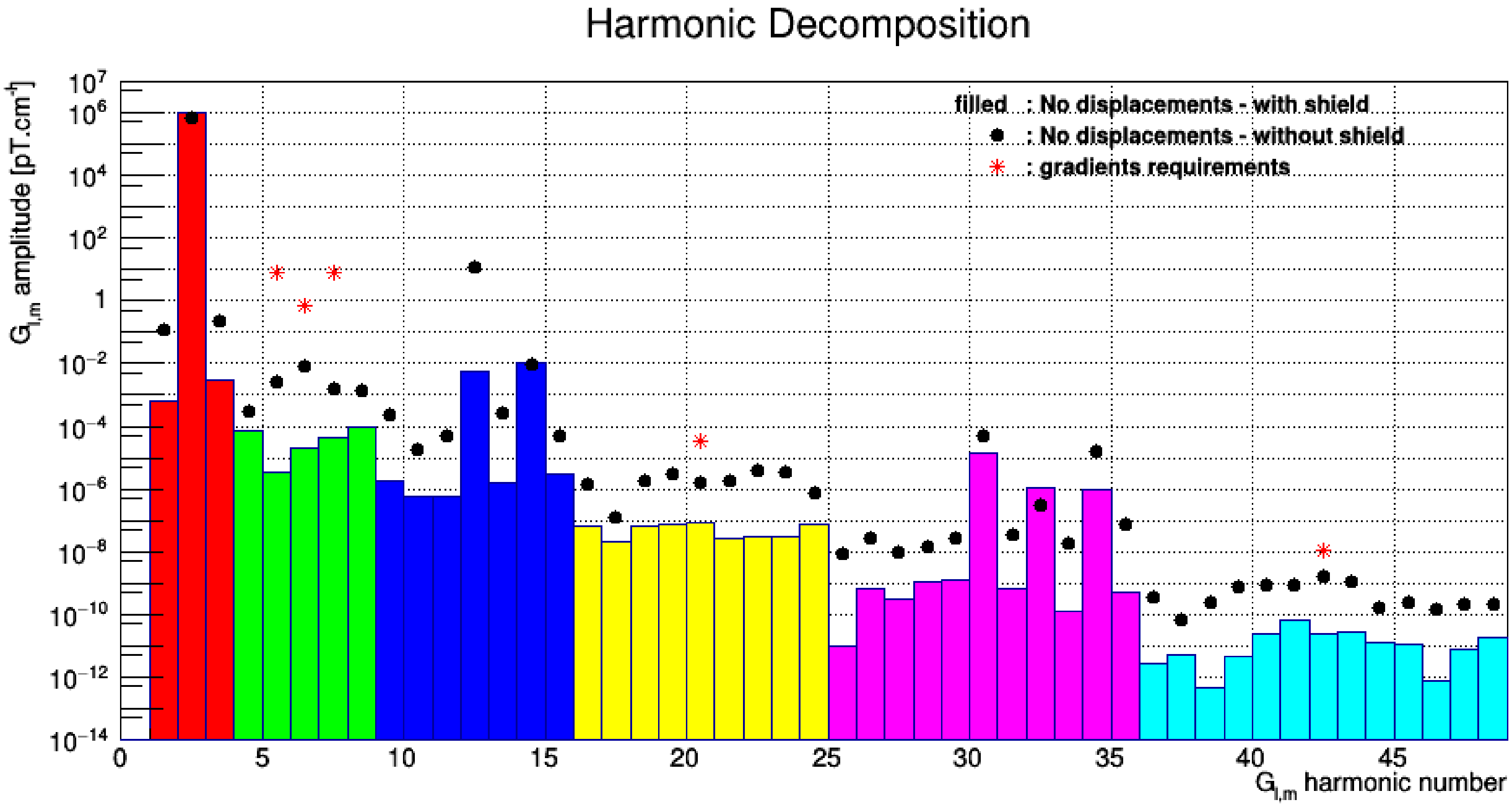
→ Ordinary relative permeability of the shield μ_r = 350,000 changed for the top & bottom layers



→ Breaks z-symmetry : $G_{1,0}$, $G_{1,2}$, $G_{3,0}$, $G_{3,2}$, $G_{3,4}$, $G_{5,0}$ etc. are allowed

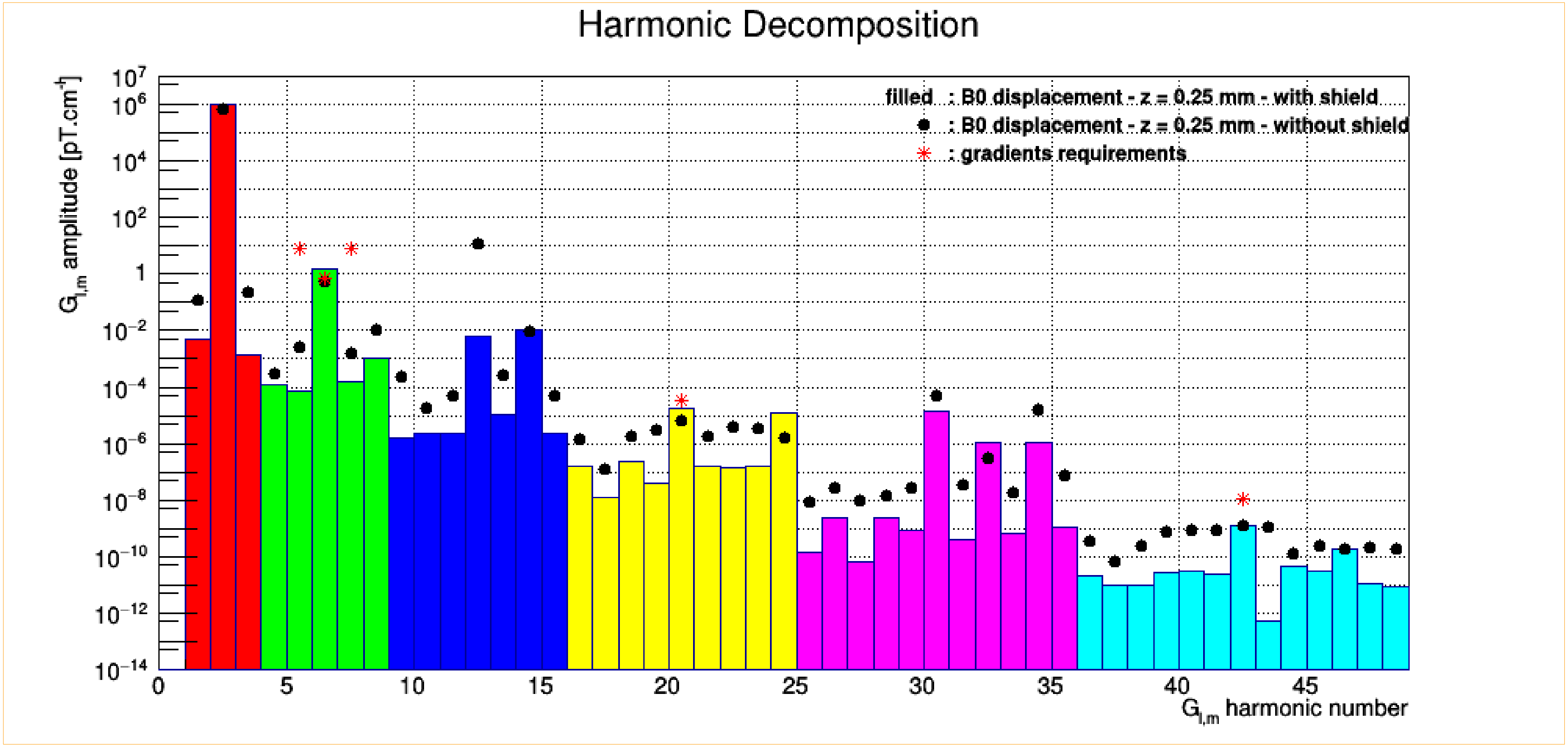
→ Even +20%/-20 % difference of permeability (μ_r(top) = 420,000 , μ_r(bottom) = 280,000) stays under requirements (but close to it)

Displacement of the B_0 coil with and without shield



→ Without shield, Global loss of uniformity (all gradients become bigger) ;

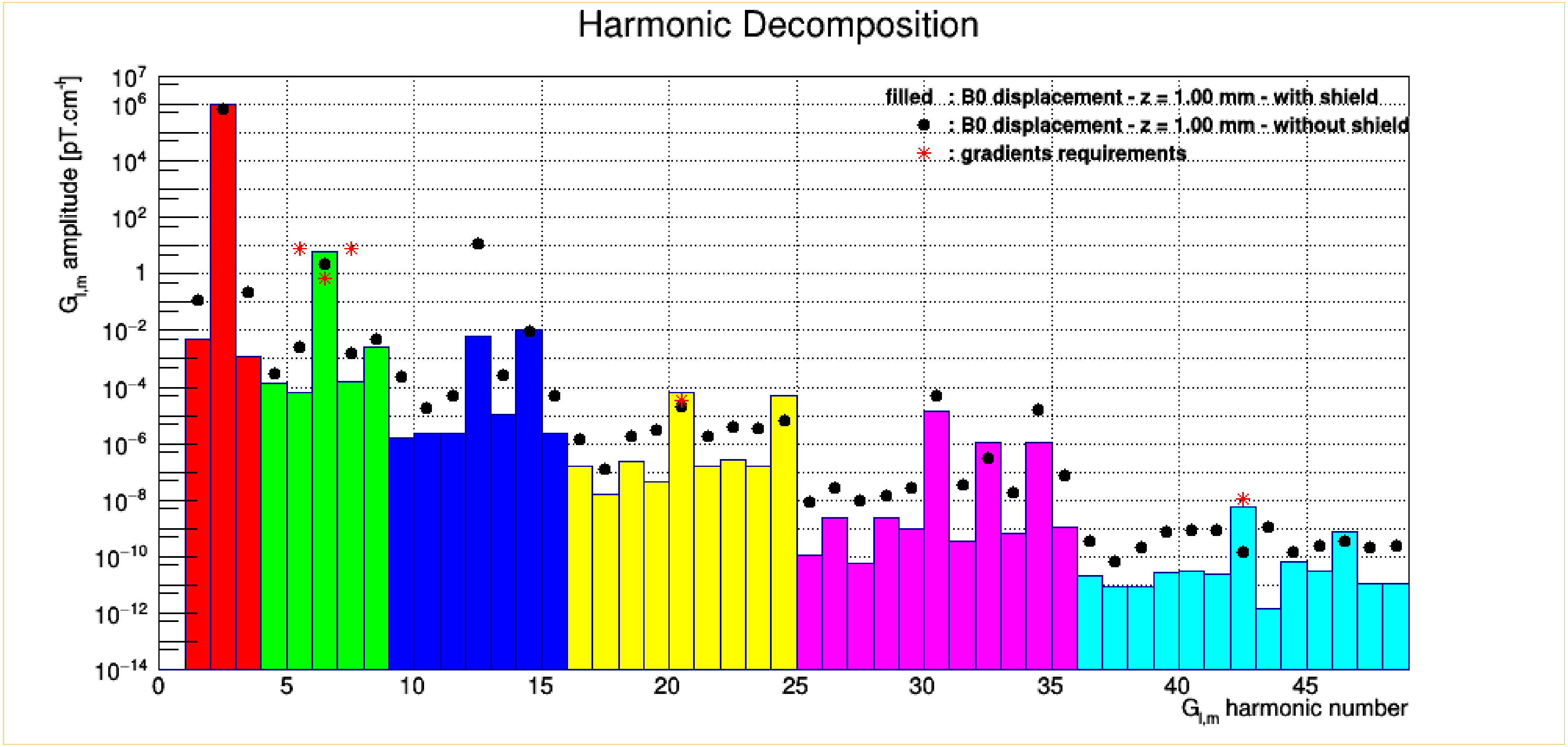
Displacement of the B_0 coil with and without shield



→ Displacement of z = 0.25 mm without shield

↳ A little bit under the requirements for $G_{1,0}$

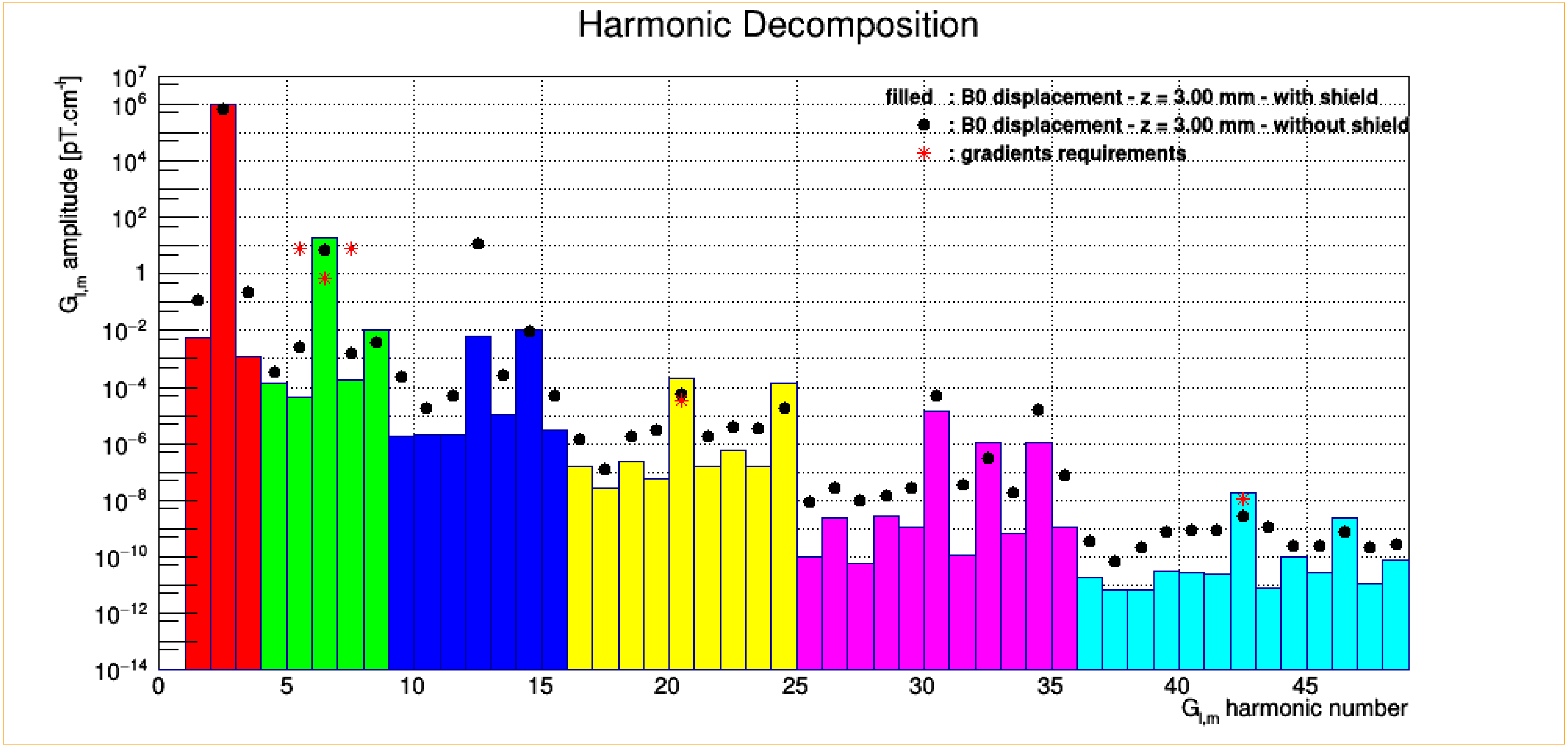
Displacement of the B_0 coil with and without shield



→ Displacement of z = 1.00 mm without shield

└→ A little bit under the requirements for $G_{3,0}$

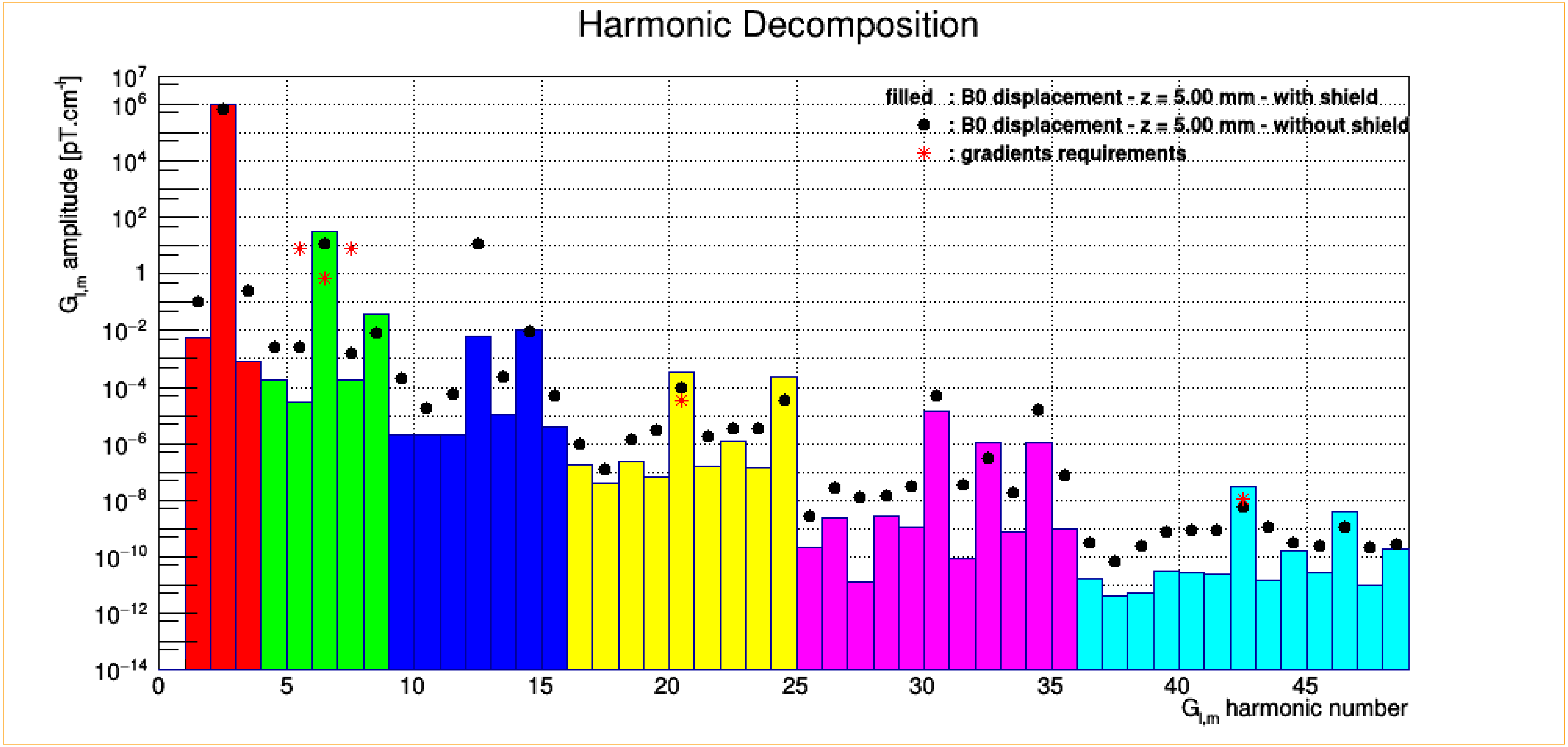
Displacement of the B_0 coil with and without shield



→ Displacement of z = 5.00 mm without shield

↳ A little bit under the requirements for $G_{5,0}$

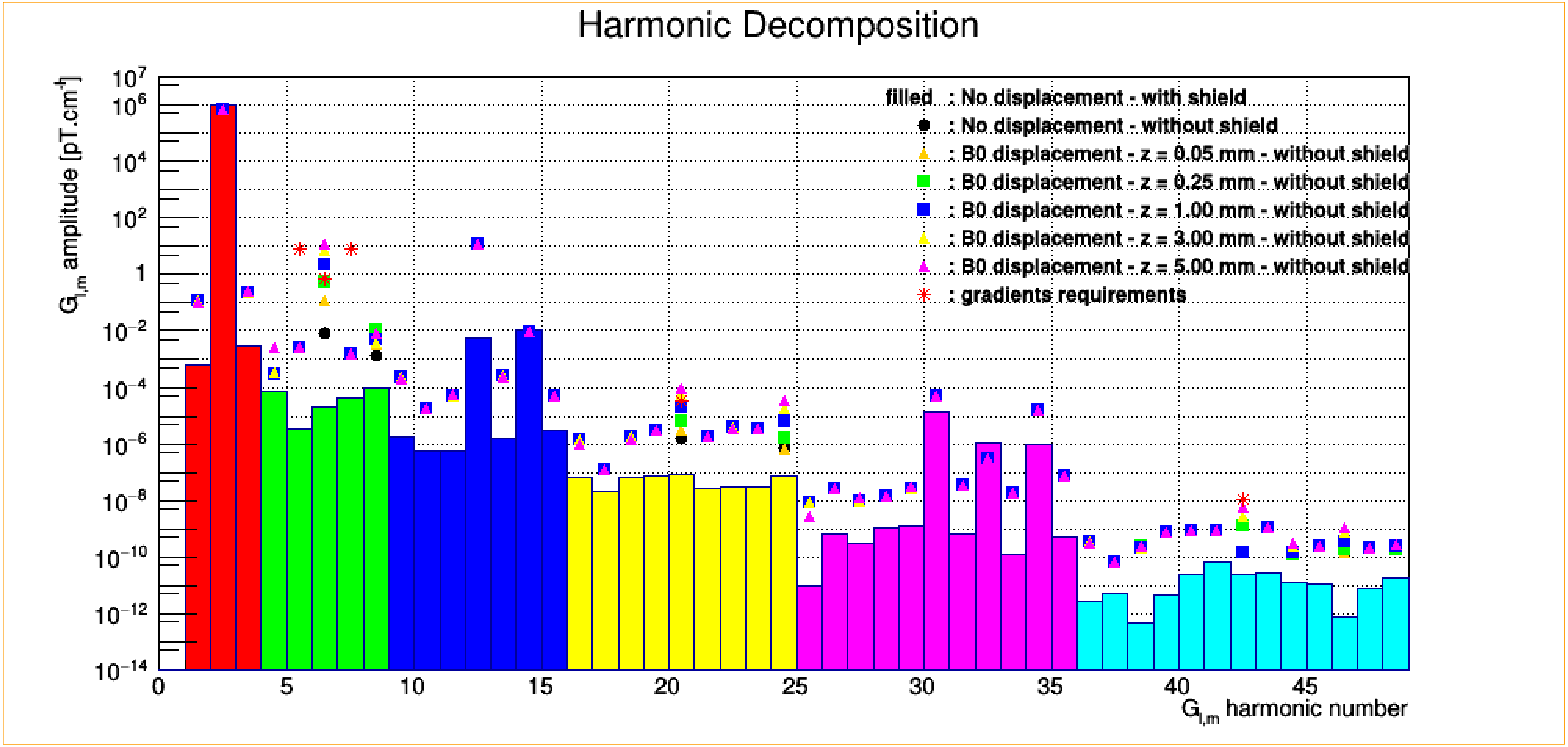
Displacement of the B_0 coil with and without shield



→ Displacement of z = 5.00 mm without shield

└→Still under the requirements for $G_{5,0}$

Displacement of the B_0 coil with and without shield



→ Without shield, Global loss of uniformity (all gradients become bigger) ;

→ But weaker dependence on the global B_0 coil vertical displacement

↳ Modifying coil-shield distance may help to reduce this dependence

Basis of harmonic polynomials (up to l=2)

l	m	H_x	H_y	H_z	n°
0	-1	0	1	0	1
0	0	0	0	1	2
0	1	1	0	0	3
1	-2	y	x	0	4
1	-1	0	z	y	5
1	0	-x/2	-y/2	z	6
1	1	z	0	x	7
1	2	x	-y	0	8
2	-3	2xy	x^2-y^2	0	9
2	-2	2yz	2xz	2xy	10
2	-1	-xy/2	$(x^2+3y^2-4z^2)/4$	2yz	11
2	0	-xz	-yz	$z^2-(x^2+y^2)/2$	12
2	1	$(3x^2+y^2-4z^2)/4$	-xy/2	2xz	13
2	2	2xz	-2yz	x^2-y^2	14
2	3	x^2-y^2	-2xy	0	15

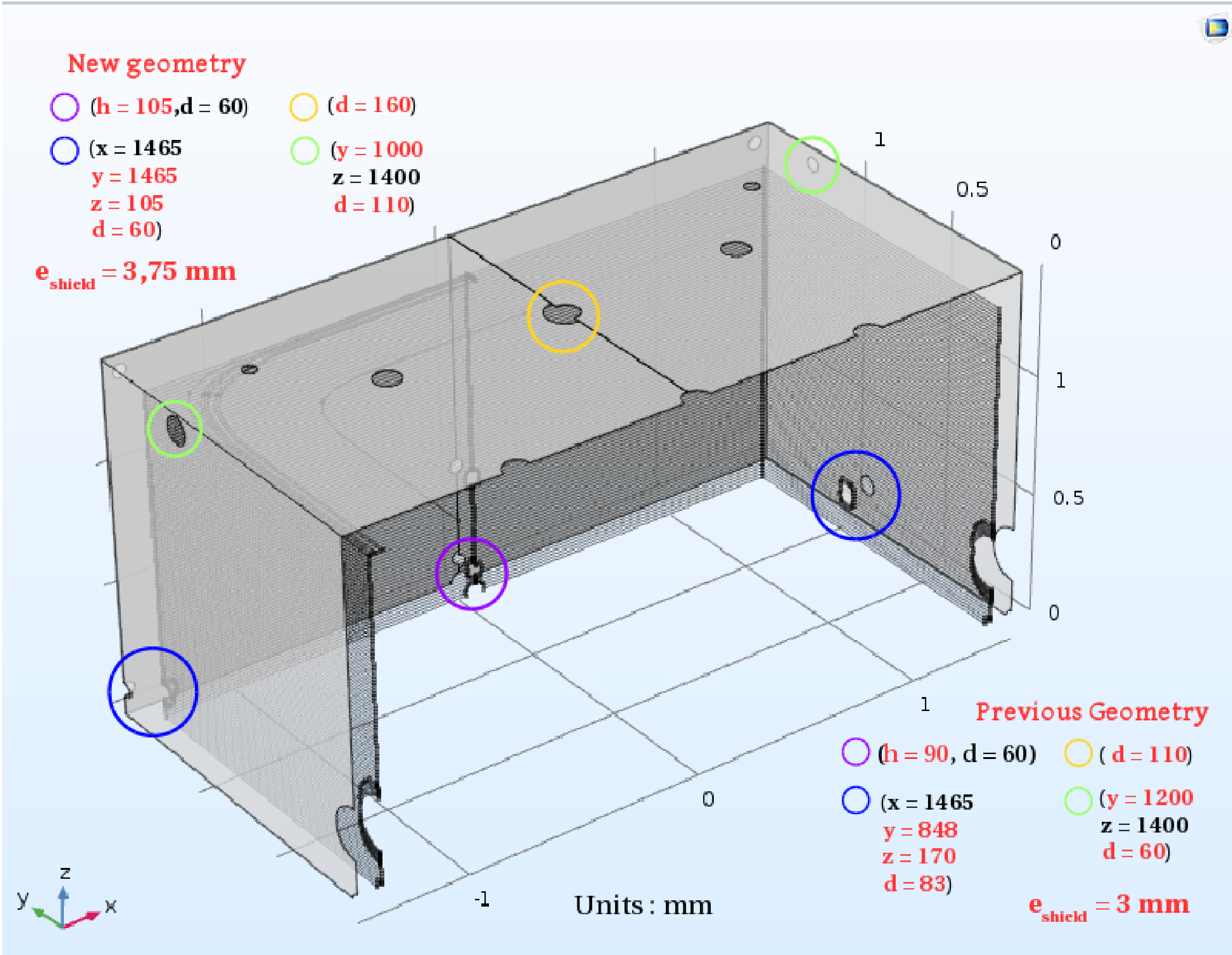
l= 0 l= 1 l= 2

Summary of allowed gradients (up to l=2)

l	m	X	Y	Z	Y & Z	X & Z	Y & X	all	n°
0	-1	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	1
0	0	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	2
0	1	Forbidden	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	3
1	-2	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	4
1	-1	Allowed	Forbidden	Allowed	Forbidden	Allowed	Forbidden	Forbidden	5
1	0	Allowed	Allowed	Forbidden	Forbidden	Forbidden	Allowed	Forbidden	6
1	1	Forbidden	Allowed	Allowed	Allowed	Forbidden	Forbidden	Forbidden	7
1	2	Allowed	Allowed	Forbidden	Forbidden	Forbidden	Allowed	Forbidden	8
2	-3	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	9
2	-2	Forbidden	Forbidden	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	10
2	-1	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	11
2	0	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	12
2	1	Forbidden	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	13
2	2	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	14
2	3	Forbidden	Allowed	Forbidden	Forbidden	Forbidden	Forbidden	Forbidden	15

Allowed gradients (green) Forbbiden Gradients (red)

Geometrical modification since Feb. 2017

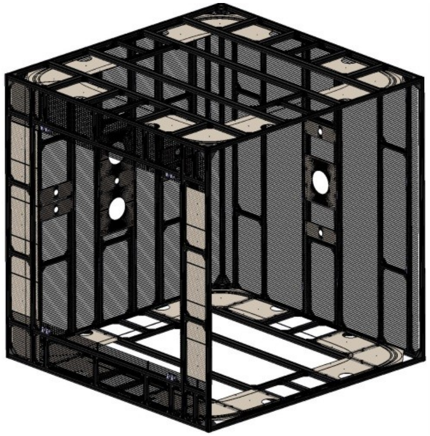


Details on mechanical solutions

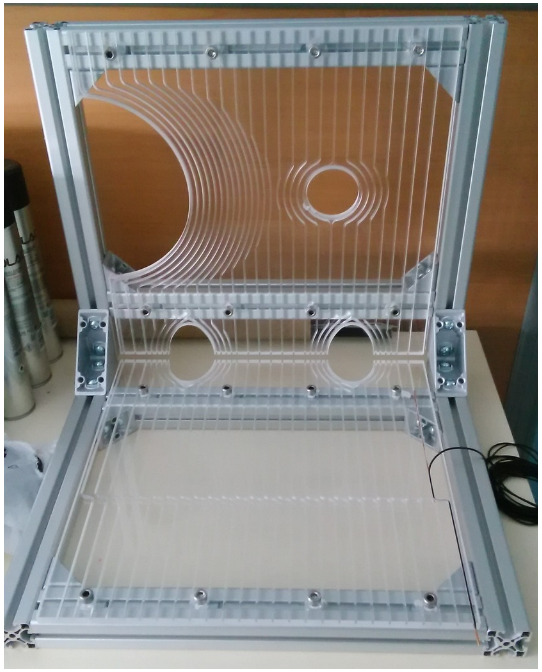
Comparative Mechanical Design

4 Different way to do :

PCB	Plexiglass (Wire on grooves)	PCB + Tube (Tube for straight wire)	Plexiglass + Tube
Copper thickness 0,075 <?<0,4mm Width max 10mm (limited by screws)	**Wire ø1,5mm (1,7mm²)**	Wire ø1,5mm on tube ø2,5mm internal (Carbon or Fiber glass) Copper thickness 0,4mm may be possible	**Wire ø1,5mm (1,7mm²)**
Big size PCB **⇒No many company / Technic limit** **⇒Cost ??**	**Small grooves to mill** (Width 2mm) Each side divided by 6 possible	Small size PCB **⇒Easy to build** **⇒Cost**	Small size Plexiglass **⇒Easy to build** **⇒Cost**
Each side divided by minimum 6 panel + Linking on corner **⇒Many welded connection (> 1500)**	**0 Welded connection**	Some welded connection	**0 Welded connection**
120 Kg PCB (+ 400Kg framework)	**450 Kg plexiglass** 32 Kg copper (+ 400Kg framework)	50 Kg < 32 Kg copper (+ 400Kg framework)	> 50 Kg (Plexi + tube) 32 Kg copper (+ 400Kg framework)
Easy to install	**Need very long time to install**	Need long time to install	Need long time to install
Sample for magnetic test ??	**Easy to check at PTB**	**Many parts to check at PTB (1200 tubes)**	**Many parts to check at PTB (1200 tubes)**
Very good position accuracy	Good position accuracy		**Less accurate solution**



Without door and right panel

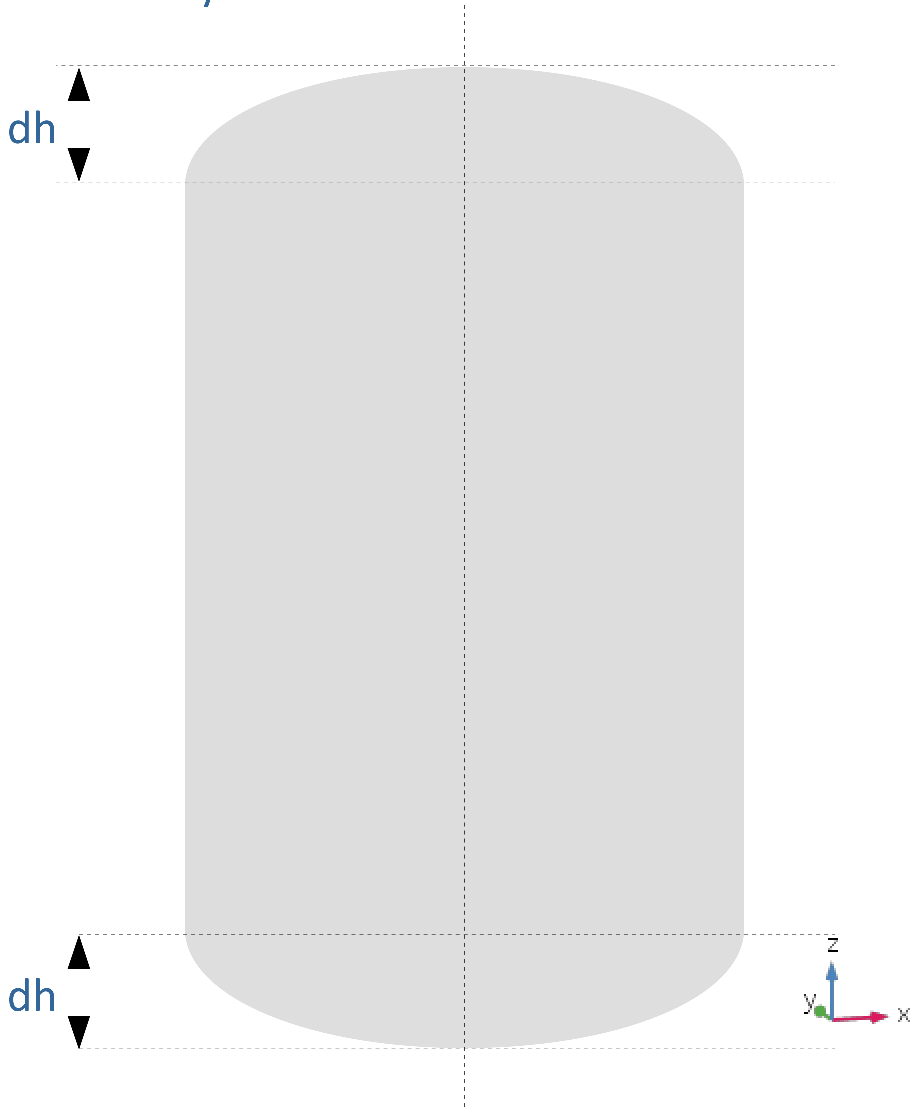


Plexiglass prototype

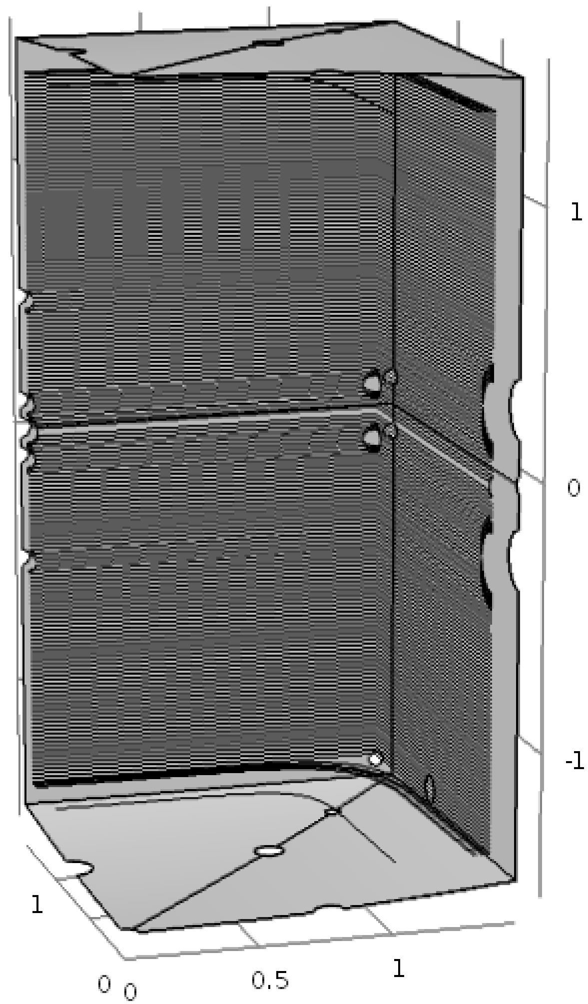
From Damien Goupillière , 31/05/2017

Shield deformation

Symetric way

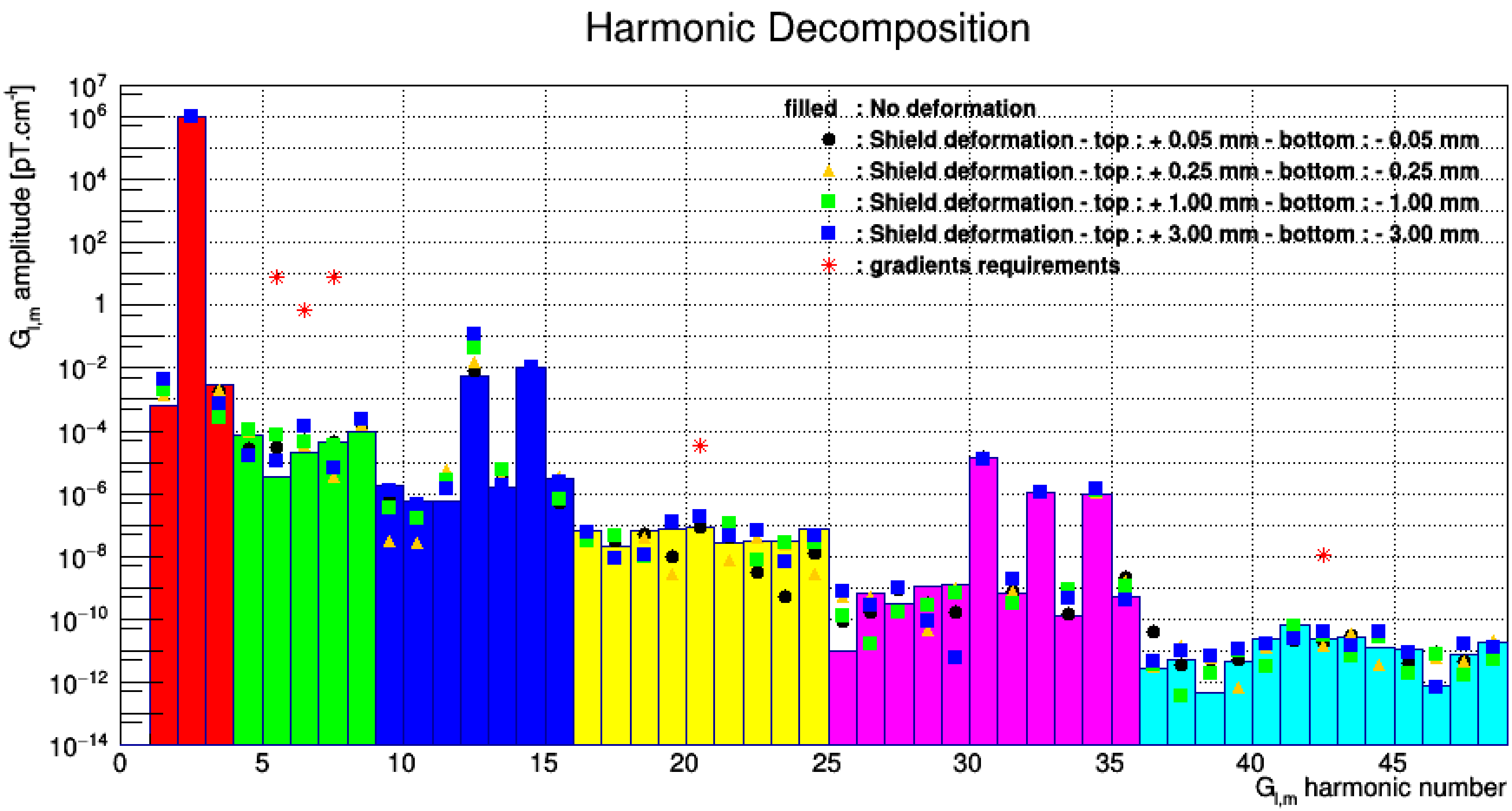


Dh = +6,5 cm



Shield deformation

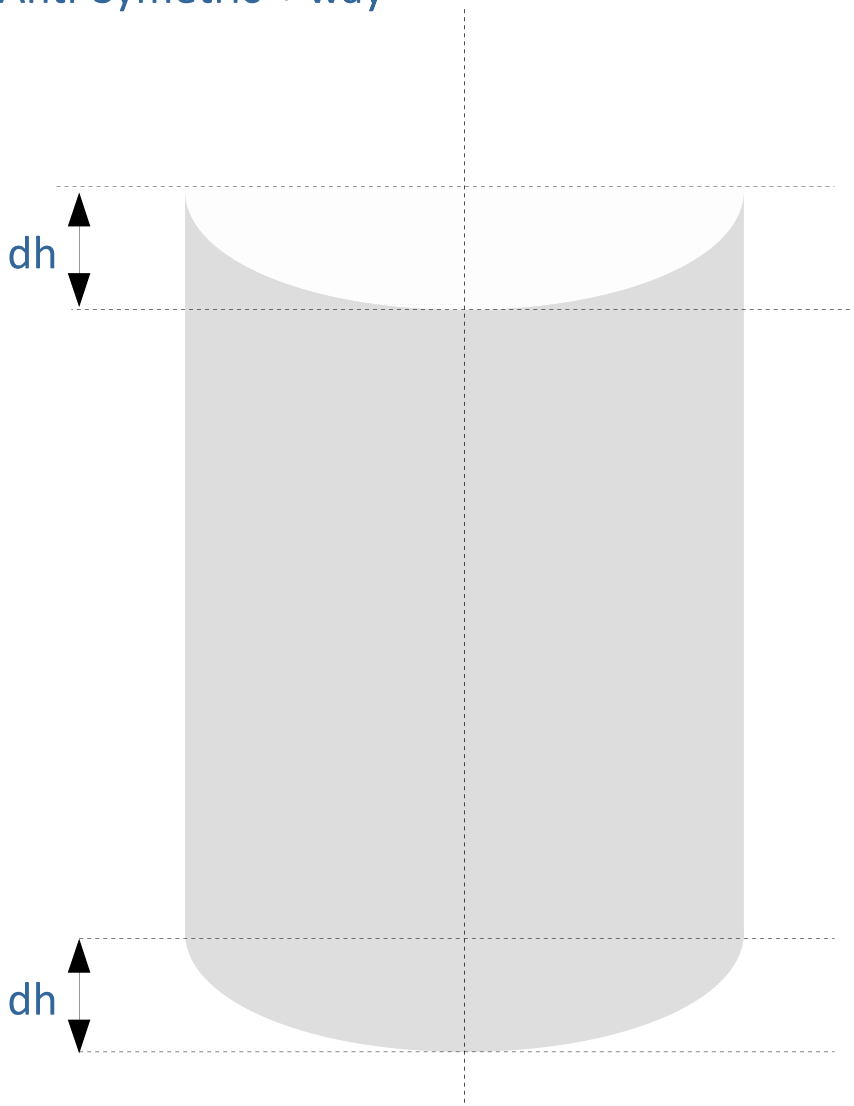
Symetric way (only 1/8th in the simulation)



→ $G_{2,0}$ increases , up to ~10 $pT.cm^{-2}$ for a symetric shield deformation of 3,00 mm

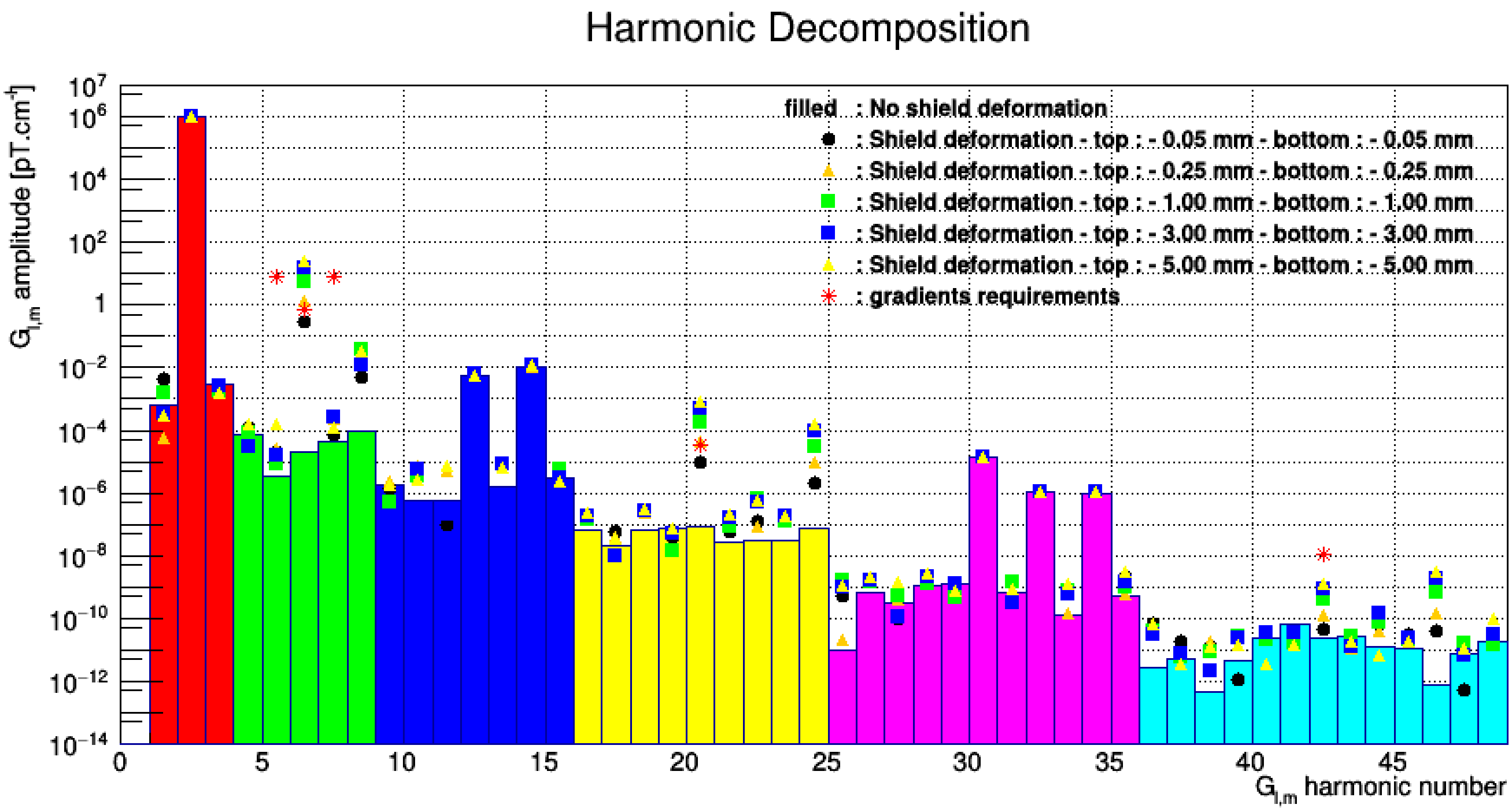
Shield deformation

« Anti-Symetric » way



Shield deformation

« Anti-Symetric » way



→ $G_{1,0}$ requirements exceeded with 0,25 mm deformation

Neutron depolarisation

Depolarisation (PRA 49 MC Gregor (1994), Roccia PhD) :

$$\frac{1}{T_2} = \underbrace{\frac{1}{2T_{1,murs}}}_{\text{Due to wall collisions}} + \underbrace{\frac{1}{2T_{1,magn}}}_{\text{Horizontal gradients}} + \underbrace{\frac{\gamma^2 L^4}{120D}\left[\frac{\partial Bz}{\partial z}\right]^2}_{\Gamma_z} + \underbrace{\frac{7\gamma^2 R^4}{96D}\left[\frac{\partial B_z}{\partial y}\right]^2}_{\Gamma_y}$$

Where L is the chamber height, R, the radius of a cylindrical chamber and D the diffusion coefficient

$T_{1,walls}$ $\approx$5000 s . Depends on the wall surface quality

$$\frac{1}{T_{1,magn}} = D\frac{|\vec{\nabla} B_x|^2 + |\vec{\nabla} B_y|^2}{B^2}$$

Cette formule, établie pour des gaz [52] est aussi valable pour un gaz de neutrons ultra-froids sous la condition de définir le coefficient de diffusion par $D = v_{xy}\frac{\lambda}{3}$ [67] où v_{xy} est la vitesse moyenne des neutrons dans le plan transverse au champ magnétique et λ est le libre parcours moyen des neutrons. Cette contribution est très faible car elle est supprimée par la valeur du champ principal au carré.

Very weak contribution

For the same amplitude of vertical and horizontal gradients :

$$\frac{\Gamma_z}{\Gamma_y} = \frac{4}{35}\cdot\left(\frac{L}{R}\right)^4$$ = 0.7 % with L = 12 cm and R = 23,5 cm

→ Depolarisation mainly due to horizontal gradients of vertical componant B_z

→ n2EDM requirements : ($\partial B_z/\partial x$), ($\partial B_z/\partial y$) < 8 pT.cm^{-1}

RF pulse + Vertical gradient

The two chambers shares the same RF pulse

If there is a vertical gradient, $<B_{top}> \neq <B_{bottom}>$

→ « working points » are different

→decrease of sensitivity

n2EDM requirement : $<\partial Bz/\partial z> < 0.7$ $pT.cm^{-1}$

Systematic effects

Uncompensated field drift :

Time variation of vertical gradient which can't be corrected

gravitational shift. The false EDM due to a correlated part of the gradient $\delta G(E)$ reads:

$$\delta d_n = \frac{\hbar \gamma_n}{4E}(h^B - h^T)\delta G(E). \quad (17)$$

The goal for n2EDM is to have this systematic effect under control at the level of $5 \times 10^{-28}\, e\cdot$cm. Assuming $E = 15$ kV/cm, and $h^B - h^T = 0.1$ cm, this corresponds to a control over the correlated part of the gradient at the level of $G(E) \leq 200$ fT/m.

Motional false EDM :

The motion of a particle inside a non-uniform static field also creates a false EDM

For large scale B non-uniformities, We have up to cubic terms

$$d^{\text{False}}_{\text{Hg}\to\text{n}} = \frac{\hbar \gamma_n \gamma_{\text{Hg}}}{32c^2} D^2 \left[G_{1,0} - G_{3,0}\left(\frac{D^2}{8} - \frac{3H'^2 + H^2}{4} \right) \right].$$

- Partially corrected by the crossing point technique

$$d^{\text{False}}_{\text{Hg}\to\text{n}} = \frac{\hbar \gamma_n \gamma_{\text{Hg}}}{32c^2} D^2 \left[G_{\text{Hg}} + G_{3,0}\left(\frac{D^2}{16} + \frac{H'^2}{2} \right) \right].$$

With the correction $G_{\text{Hg}} = G_{1,0} + \frac{1}{16} G_{3,0}(4H'^2 + 4H^2 - 3D^2).$

Leading to n2EDM requirements for $G_{3,0} < 3.3 \times 10^{-5}$ pT.cm^{-3}

and $G_{5,0} < 1.1 \times 10^{-8}$ pT.cm^{-5}